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PETROLOGY AND GENESIS OF A URANIUM-BEARING SYSTEM  
OF PEGMATITE DIKES, NANCY CREEK AREA,  
NORTHEASTERN WASHINGTON

by

William C. Beyer

A.B., Dartmouth College, 1975

Presented in partial fulfillment of the  
requirements for the degree of

Master of Science

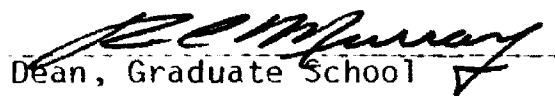
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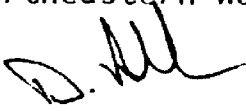
## ABSTRACT

Beyer, William C., M.S., Winter, 1981

Geology

Petrology and Genesis of a Uranium-bearing System of Pegmatite Dikes, Nancy Creek Area, Northeastern Washington

Director: David Alt



The Nancy Creek area lies on the eastern flank of the Kettle Dome, 10 kilometers northwest of Kettle Falls, Washington. A system of granite dikes intruded the Precambrian metamorphic rocks of the dome during a cataclastic event that marked the formation of the dome. The dikes vary in texture from aplitic to pegmatitic. Anomalous uranium occurs in garnet-bearing pegmatitic dikes in an amphibolite. Beta uranophane replaces the primary uranium mineral uraninite. Field relationships and petrographic evidence show the magma for the dikes came from neither local metamorphic segregation nor local anatexis. No obvious igneous source crops out. The genetic source must lie "at depth". A batholithic core to the dome may be postulated, as plutons crop out along its western and southern margins, and within the dome. This provides a convenient magma source. This author prefers a genesis through metamorphic anatexis. During emplacement of the dome, removal of the overlying strata drops the lithostatic pressure, causing a decrease in the melting temperature of undersaturated granitic melts and an increase in the relative activity of water. These combine to allow a greater amount of partial melting to occur at a constant temperature, producing the magma for the dikes. Uranium preferentially partitions into the melt along with the water. Crystallization processes and partitioning of uranium into the volatile stage concentrate the uranium into the pegmatites.

## ACKNOWLEDGMENTS

I would like to thank Energy Fuels Nuclear for financial and logistical support of the field work and for permission to make my findings public. John Nelson and Jeff Stimson lent their experience and assistance. Dave Alt and Don Hyndman contributed greatly appreciated insights and critical assessments to this thesis. Jeff Lelek and Jim Harrington provided lively and valuable discussions. I especially would like to thank Cathy Boag for her unending encouragement and support.

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## CHAPTER I

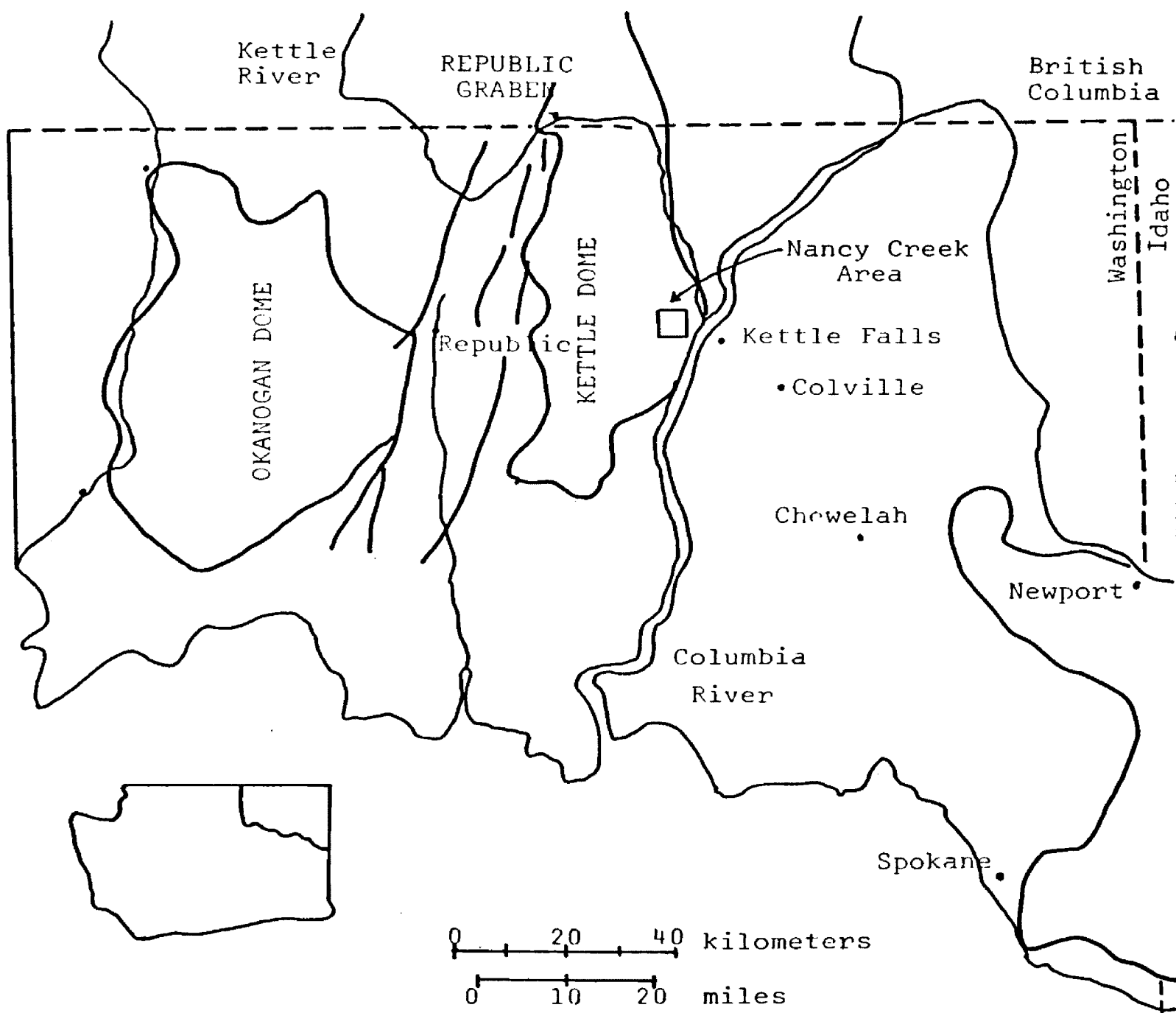
### INTRODUCTION

The Nancy Creek area lies on the eastern flank of the Kettle Dome, five miles northwest of Kettle Falls, Washington (Fig. 1). Gently folded metamorphic rocks of the dome (Cheney, 1979) contain locally abundant uranium-bearing pegmatitic granite dikes. Granite dikes are typically thought of as originating from an igneous source. In metamorphic rocks, other possible genetic processes for dikes such as anatexis and metamorphic segregation must be considered. Uranium commonly occurs as primary uraninite in late-stage igneous dikes, as magmatic processes may concentrate the uranium into late stages. Metamorphic processes, on the other hand, are usually considered to be dissipators, not concentrators in ore deposit genesis. These processes do concentrate water and potassium for example, into certain phases. Given the proper chemical conditions, uranium tends to be mobile, and may mimic the movement of potassium. Consequently, a genetic process for uraniferous pegmatitic dikes in metamorphic rocks must consider both metamorphic and igneous processes.

Field relationships and textures indicate the majority of the dikes intruded the exposed metamorphic section during a shearing event. This shearing produced cataclastic textures along the eastern margin of the Kettle Dome, and marked the emplacement of the dome. Removal of much of the overlying section would accompany this emplacement, dropping the

Figure 1

Metamorphic Provinces in Northeastern Washington and  
the Location of the Nancy Creek Area



lithostatic pressure. The melting temperature for undersaturated melts would fall with the drop in pressure, and anatexis could occur in the metamorphic rocks of the dome below the present level of exposure. Uranium and water would preferentially partition into the melt, producing a wet, uranium-enriched magma for the dikes.

Crystallization processes tend to concentrate uranium into the late magmatic stages, along with the volatiles. The volatile-rich stages moved into the amphibolite where the shearing had fractured this brittle rock and produced a preferred environment. Further crystallization of the magma produced pegmatitic textures in uraniferous dikes.

### Regional Geology

The Omineca Crystalline Belt, an area of metamorphic and igneous rock that includes the Shuswap metamorphic complex, extends from British Columbia into north-central and northeastern Washington. The Kettle Dome, a region 70 km north-south by 30 km east-west, of gently folded metamorphic rocks in northeastern Washington, lies on the southeastern end of this belt. It has been structurally (Donnelly, 1979; Lyons, 1967) and petrographically (Cheney, 1977, in press; Parker and Calkins, 1969) related to Shuswap rocks. The Republic Graben separates it from the Okanogan dome to the west (Fig. 1). To the east, a shear zone separates it from layered sedimentary and volcanic rocks. Bowman (1950) described this shear zone as a normal fault with 14,000 feet of throw in order to account for the juxtaposition of metamorphic and non-metamorphic rocks. Cheney (in press) reinterprets it as a decollement.

Campbell (1937,46) included the Kettle Dome in the "Colville batholith", adding it to the batholith of Krauskopf and Waters (1941) and Pardee (1918). These earlier authors restricted the "batholith" to the west side of the Republic Graben, or to the present Okanogan Dome. Snook (1965) reinterpreted the protoclastic batholithic border of Krauskopf and Waters (1941) as granitic gneisses formed during regional metamorphism, followed by mylonitization and gentle folding. He decided that no batholith existed. Fox and others (1976) reconciled these polarized viewpoints, and called the area a gneiss dome with a molten core and a partially magmatic mantle.

As an extension of this argument, the Kettle Dome also is not a batholith, and it is also not a true gneiss dome. Cheney (1979) interprets the dome as gently folded sequence of Precambrian metamorphic rocks. He claims it formed during a post-Eocene folding event. Cataclasis and thrusting occurred immediately before or during folding. Metamorphism began probably in the late Cretaceous and culminated as emplacement of the dome started. Metamorphic rocks show a biotite K-Ar cooling date of  $50.4 \pm 1.4$  m.y. b.p. (Engels and others, 1976), roughly synchronous with the dome emplacement.

Armstrong (1979), modeling the emplacement of core complexes in the eastern cordillera, deformed a thinned and weakened lithosphere. Crustal shortening thickened this zone, which rose upward as it contracted at depth. The cover rocks flattened and were pushed eastward to form fold and thrust belts. Fox and others (1977) do not differ drastically in

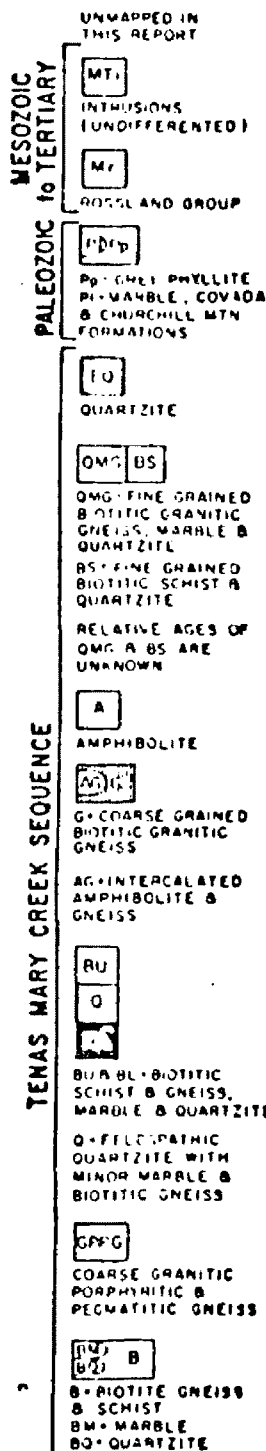
their scenario for emplacement of the Okanogan dome during compression, but they do differ drastically in the heat source that causes the thinning and drives the model. They depend on an overridden spreading center for their heat, while Armstrong relies on eddies formed in the "trapped asthenospheric mantle" above the descending oceanic slab. The Okanogan Dome, with its abundant magmatic activity sits near the center of this thermal high. The Kettle Dome, on the edge of this crystalline terrane, forms a cooler analogue of the same deformational event.

### Structure of the Kettle Dome

The regional map of the Kettle Dome (Cheney, in press; Donnelly, 1978) (Fig. 2) show the dome as one large anticlinal fold, with strata of consistent dips on either limb. The metamorphic layers in the study area near Nancy Creek strike within  $10^\circ$  of north, paralleling the metamorphic and cataclastic foliations. Dips vary from  $5-19^\circ\text{E}$  and average  $12^\circ\text{E}$ .

Donnelly (1978), studying small-scale fold features, recognized four fold phases in the metamorphic rocks south of Nancy Creek in an area that overlaps this thesis. His analysis show tight to isoclinal, recumbent to overturned  $F_1$  folds formed as a ductile reaction to  $D_1$ , a flat shearing stress. As the metamorphic peak waned and rock properties changed,  $D_1$  formed cataclastic textures.  $D_2$  produced upright gentle folds and asymmetric concentric or boxfolds ( $F_2$ ), and kinks and crenulations ( $F_3$ ) all overturned to the east.  $D_3(?)$  formed the youngest folds of upright, gentle to open geometries. The overall  $D_1$  deformation

(from Cheney, in press)





correlates with gneiss dome formation, and forms structures similar to folds of the Shuswap terrane (Donnelly, 1978).

## CHAPTER II

### METAMORPHIC PETROLOGY

#### Introduction

Five important rock types; 4 metamorphic units and a complex variety of granitic dikes, crop out within the study area (Plate 1). The metamorphic section consists of, from bottom to top, a quartzite-calcsilicate-marble unit, a granitic gneiss, a hornblende amphibolite, and a quartzite. No direct evidence for stratigraphic up or down, or overturning exists, so the section is assumed to be right side up. The metamorphic grade falls in the amphibolite facies as defined by Hyndman (1972) or in medium to high grade as defined by Winkler (1976).

The fifth unit of pegmatitic to aplitic granite dikes intrudes all four metamorphic units, making them the youngest unit present. Orthoclase, an albite-rich plagioclase, and quartz dominate the mineralogy. This unit constitutes the economic focus of the thesis, as it contains all known uranium anomalies.

#### Quartzite

The quartzite-calcsilicate-marble unit occurs as the structurally lowest unit exposed in the map area. It crops out only in the northwest and southwest corners of the map, covering less than 3 km<sup>2</sup>. It tends to form hillslopes with some stair-stepping topography due to resistant quartzite layers. Its best exposures lie on the southwest

side of Hoodoo Lake, and along logging roadcuts. To keep nomenclature consistent with that of Cheney (in press), this unit is referred to as simply the quartzite. The other, structurally higher quartzite will be called the eastern quartzite.

This unit consists of interbedded feldspathic quartzite, calc-silicate schists and gneisses, pelitic schists, and forsterite marbles. It correlates with Cheney's (in press) heterogeneous top of a generally more homogeneous 650 meter thick feldspathic quartzite. Quartzite and marble constitute the majority of the outcrops of the 200 meter exposed thickness, whereas the other, less resistant rock types appear only in logging road cuts. This resistance-controlled exposure makes determination of relative abundance of rock types difficult.

Feldspathic quartzite. In outcrop, the feldspathic quartzite forms small, 1-3 meter-high cliffs. Bedding, defined by intervening, continuous 1 cm-thick biotite-rich layers occurs at 7-15 cm intervals. In handsample, the rock is light to medium gray, and medium-grained feldspars form white streaks, and lenses.

On the average, the rock contains greater than 90 percent quartz, 5-10% feldspar, and 1-5% biotite and muscovite. Sillimanite needles are a minor constituent. Quartz generally occurs as anhedral, medium-grained, elongate crystals with sutured grain boundaries. Crystal elongation, paralleled by the micas, defines the foliation. The feldspar percentage consists of approximately equal parts orthoclase and plagioclase.

They are both medium to coarse grained, and anhedral. Sericite moderately to heavily alters the plagioclase, masking its twinning. Orthoclase shows little to no alteration. It does display minor secondary overgrowths which may engulf a few quartz grains along its crystal edges. This late-stage growth, and the sericitization of the plagioclase may indicate minor potassium metasomatism.

The medium-grained subhedral to anhedral micas occur in thin, 2-4 cm thick layers. They also occur along shear planes, yet show no deformation themselves. Minor, very fine-grained sillimanite(?) locally rims the muscovite. Biotite may exhibit minor retrograde alteration to chlorite.

Marble and calc-silicate gneiss. The marbles and calc-silicate layers characteristically occur together and have gradational contacts. They tend to associate with pelitic rocks, showing both sharp and gradational contacts. The thickness of individual beds ranges from 0.3 to 2 meters, with marble and calcsilicate beds combining to form layers 1 to 4 meters thick.

The marbles contain 65-95% calcite, 0-15% diopside, 0-20% heavily serpentized forsterite, and minor phlogopite and garnet. The medium to coarse grained anhedral calcite shows no preferred orientation. The medium grained, subhedral diopside and forsterite are unoriented, but form a crude band, probably a reflection of relic bedding. Linear 1-3 mm long flakes of graphite, where present, parallel this crude band. For more siliceous varieties, quartz appears with diopside, and without forsterite.

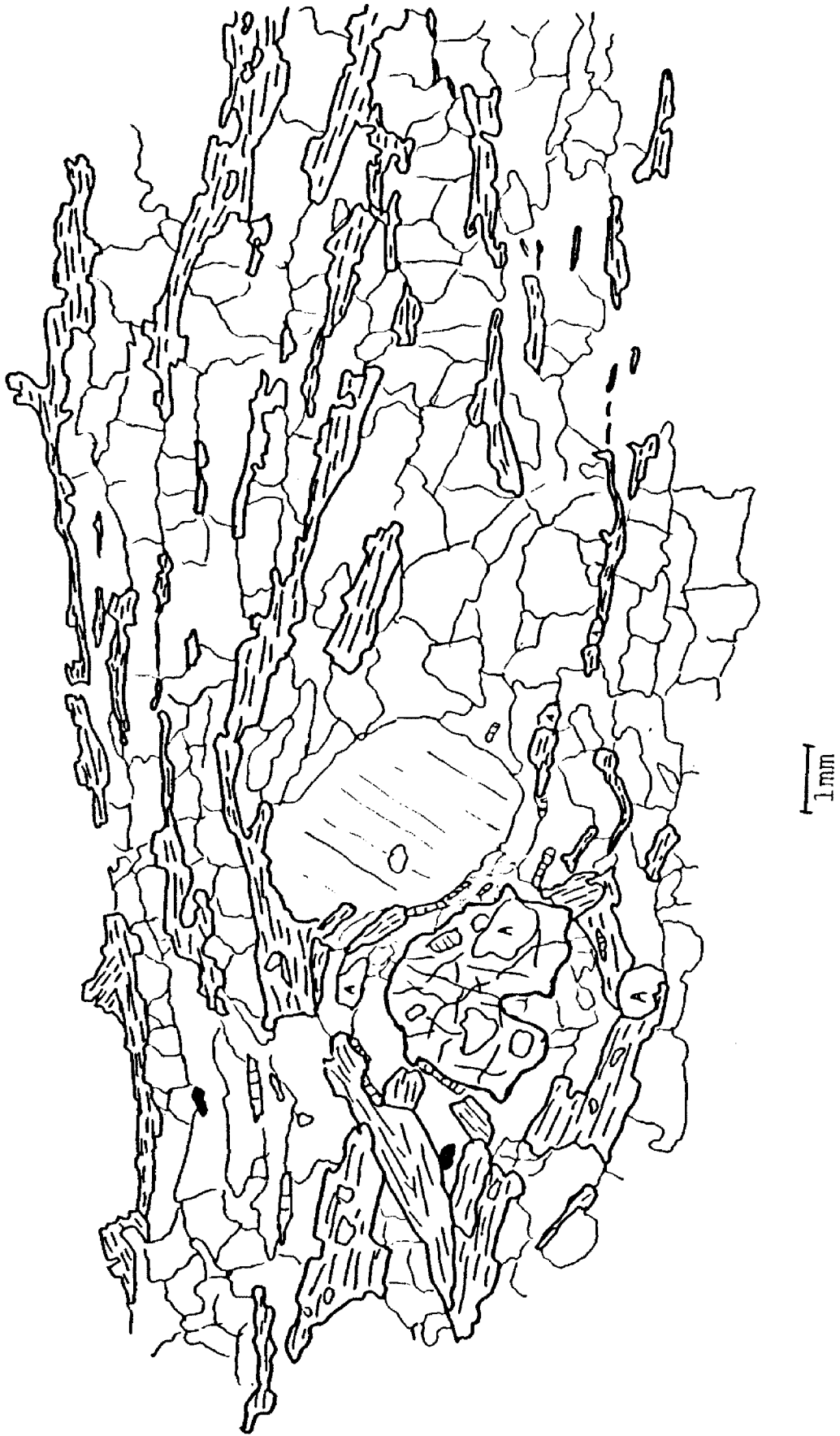
The quartz-free marbles show no cataclastic textures. In the quartz-bearing varieties, the quartz has undulatory extinction, and minor granulation of its crystal edges.

Pelitic gneisses. The quartzites grade into interlayered 1-3 meter thick pelitic gneisses. Biotite, quartz, and orthoclase constitute the major minerals, accompanied by minor plagioclase, sillimanite, muscovite, garnet, zircon, and apatite. The biotite percentage varies from 10 to 50%, quartz from 15 to 75%, and orthoclase from 5 to 35%. Biotite defines a strong foliation, further accentuated by segregated mafic and felsic layers. This foliation parallels the contacts within the quartzite unit.

Migmatitic zones appear in the pelitic layers producing felsic stringers both parallel and discordant to the foliation. Orthoclase and quartz, with minor plagioclase dominate the 0.4 to 4 cm thick felsic assemblage. The more mafic areas contain biotite, quartz, plagioclase, garnet, and sillimanite. The plagioclase ( $An_{10-20}$ ) in the felsic stringers contains less calcium than the plagioclase ( $An_{35-40}$ ) in the surrounding mafic layers.

In thin section WB-72, (Fig. 3) poikiloblastic, rolled garnets, 7-8mm in diameter, with snowball texture appear only in shear zones. They contain quartz, biotite, sillimanite, and apatite inclusions. Biotite concentrates near the garnets, fading out along the foliations. This

Figure 3. Shear zone in the Quartzite- slide WB-72



1 mm

biotite is generally fine- to medium-grained, and undeformed. Sillimanite also occurs with the biotite, commonly as grains along biotite cleavages. This habit mimics a muscovite habit found in sillimanite-free parts of the slide. Sillimanite is also limited to these shear zones. Large orthoclase porphyroblasts have grown, along with minor quartz, in the pressure shadows of the rolled garnets.

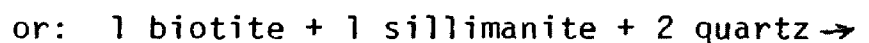
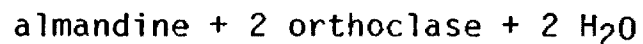
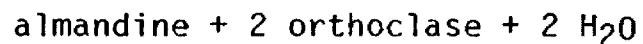
In unsheared portions of the slide, neither garnet, nor sillimanite occur. The mineralogy consists of 75% anhedral quartz with sutured grain boundaries, 20-25% well-oriented muscovite and biotite in thin layers, and 0-5% orthoclase. Muscovite is commonly intergrown with biotite along cleavage planes. It may show a very fine grained reaction rim where neighboring either quartz or orthoclase.

Only the garnet-sillimanite areas contain any retrograde effects. Chlorite and magnetite replace 25% of the biotite, and garnet also shows minor chlorite alteration. Orthoclase may display minor sericite.

Metamorphic grade. The mineral assemblages of biotite-muscovite-orthoclase in the feldspathic quartzite and calcite-calcium garnet-diopside can exist over wide temperature and pressure conditions, and do little to precisely determine metamorphic grade. However, two mineral assemblages in the pelitic rocks, almandine-biotite-orthoclase, and sillimanite-almandine-biotite-orthoclase indicate high grade (Winkler, 1976, p. 83) or sillimanite-orthoclase zone of amphibolite facies metamorphism (Hyndman, 1972, p. 354).

Referring back to thin section WB-72, unsheared portions of the rock have a biotite-muscovite-orthoclase assemblage, a medium grade of metamorphism mineral assemblage, (Winkler, 1976, p. 82), whereas sheared rock has the high-grade assemblages of almandine-sillimanite-orthoclase and biotite-almandine-sillimanite-orthoclase (Winkler, 1976, p. 82).

The directed stress along the shear planes appears to have acted as a catalyst (Spry, 1969, p. 2), causing muscovite + quartz  $\rightarrow$  sillimanite + orthoclase + H<sub>2</sub>O and probably:



As these reactions release water, a necessary ingredient for retrograde products, it may explain why retrograde metamorphism was restricted to the sheared zones.

### Biotite-Plagioclase Gneiss

A biotite-plagioclase gneiss 800 meters thick overlies the quartzite unit. It dominates the map area areally and topographically by covering 40 of the 70 square kilometers mapped and underlying the highest mountains in the area. Prominent north-south and east-west joint sets help form the blocky outcrops, prominent talus slopes and, sheer canyons up to 100 meters deep common to this unit.

This gneiss contains 30-75% plagioclase, 7-15% biotite, 8-30% quartz and 5-20% orthoclase. Hornblende, garnet, and muscovite may



contribute up to 2% each, whereas magnetite, apatite, and zircon occur only as trace minerals. Secondary orthoclase and quartz may each constitute up to 20% of the rock, causing the wide compositional range. Excluding these secondary effects, the gneiss lacks compositional banding, and contains a reasonably consistent 60-70% plagioclase, 10-15% biotite, 10-20% quartz, and 0-5% orthoclase.

The plagioclase is andesine of  $An_{45-50}$ . Its anhedral grains typically measure 0.3 to 1.5 mm across. Secondary albite-rich rims produce normal zoning. These rims may be poikilitic. Quartz occurs as single grains with biotite and plagioclase, and in quartz stringers and quartz-orthoclase-garnet veinlets. It is anhedral, 0.3-0.6 mm in diameter, and generally has sutured grain boundaries and undulose extinction. Subhedral to euhedral biotite laths from 0.1 to 0.8 mm long occur as unoriented grains in oriented clusters. The biotite may contain rare zircon. Muscovite, where present, occurs with biotite, either along biotite cleavage planes, or near it and with the same habit.

Orthoclase has two distinct habits. In one, it appears as a primary gneiss mineral, 0.3 to 0.7 mm in diameter, closely resembling plagioclase. In the other habit, it forms coarse, 0.8 to 3.0 mm in diameter, often poikilitic porphyroblasts situated in veinlets with quartz, or as separate, individual crystals. Where poikilitic, they may contain quartz, plagioclase, and biotite inclusions.

Accessory minerals characteristically comprise 1 to 2% of the rock, but may run as high as 5%. In decreasing order of abundance they are apatite,

magnetite, red garnet, zircon, and sphene. They all occur as sub-hedral to euhedral, interstitial grains. Zircon and magnetite may be enclosed in biotite. The quartz-orthoclase veinlets contain most of the garnet.

Three features combine to form a prominent foliation. The parallel clumps of biotite define the primary foliation. Cataclastic textures, where present, parallel and emphasize the primary foliation. The quartz-orthoclase veinlets, and lineations of secondary porphyroblasts parallel these two, and were controlled by them. Without these two secondary effects, the primary foliation would be weak, and in some areas, almost unnoticeable. Close scrutiny, however, reveals its pervasive presence.

The biotite-plagioclase gneiss contains ubiquitous cataclastic textures. They run the gamut from undulose extinction and minor granulation of quartz to well-developed flaser textures. In general, their intensity varies inversely with depth. Cataclastic zones do not, however, have an even distribution as relatively unaffected layers separate sheared zones.

In the flaser textures, porphyroclasts of plagioclase and orthoclase sit in a matrix of crushed quartz and feldspars. The porphyroclasts are generally rounded, as if their corners broke off. In extreme cases, just short of being mylonitic, the matrix constitutes 80% of the rock. In the matrix, quartz shows extreme granulation, sutured grain boundaries, and undulose extinction. Feldspars have bent twin planes, and a distorted extinction. Biotite tends to concentrate in the matrix. It orients well with the cataclastic texture, and follows the matrix, where it bends around the feldspar augen. The biotite grains have straight, unbroken

cleavage planes, even where it is either entirely surrounded by granulated matrix or in layers that wrap around the porphyroclasts. This indicates recrystallization subsequent to the cataclasis.

Orthoclase porphyroclasts commonly show secondary growth, as they have engulfed granulated matrix grains along their edges. Plagioclase may show this same feature in sodium rich rims, though not as commonly. This addition of material coincides temporally with the cataclastic event.

In less extreme varieties of cataclastic textures, crushed material is limited to 3-6mm-thick layers separating relatively undisturbed areas. Where crushed layers are absent, shear planes and undulose extinction remain to indicate the presence of deformation. In this gneiss, the planar cataclastic textures parallel the primary foliation.

### Amphibolite

A black amphibolite lies above the biotite-plagioclase gneiss. Unlike the underlying gneiss, the amphibolite forms gentle slopes. In hand sample, this foliated rock varies from homogeneous to conspicuously layered with 1-2mm-wide white layers separated by 3-6mm-wide dark layers paralleling the foliation. Black hornblende dominates the color, whereas plagioclase forms the white layers and adds a speckled appearance to the homogeneous amphibolite.

In thin section, the rock typically contains 60-65% hornblende, 30-35% plagioclase (An<sub>50-60</sub>), 2-5% sphene, 0-3% diopside, and a trace to 1% magnetite. The hornblende forms a 5 to 2mm-long subhedral lath. They are well oriented with sub-parallel crystallographic axes, and define

the foliation. They exhibit light- to dark-green pleochroism with  $\alpha =$  light green,  $\beta =$  dark green, and  $\gamma =$  darker green. The plagioclase occurs as equidimensional, anhedral crystals 0.25 to 0.6mm in diameter. Where present, crystal elongation parallels the hornblende foliation.

Plagioclase segregations form the white layers with grains that are coarser (0.6 to 1.5mm in diameter), and slightly more euhedral than elsewhere. Their anorthite content, however, does not differ. Hornblende forms a continuous coarse grained, 1-2mm thick border zone on both sides of the layers. This border zone grades quickly back into a more homogeneous rock. Mixing the white layer and its border produces mineral percentages similar to the rest of the rock. This, plus the constant plagioclase content, suggests metamorphic segregation created the layers.

Diopside occurs as 0.3 to 1.0mm in diameter anhedral crystals unevenly distributed as crude clumps. The unusually abundant sphene appears mainly as subhedral, 0.05 to 0.2mm-long wedges. Its crystal form varies widely from euhedral wedge-shaped crystals to anhedral, rounded grains. It occurs evenly distributed in the rock as crystals either interstitial to, or included in hornblende. Their long axes parallel the foliation. Magnetite, the only opaque mineral, forms inclusions 0.05 to 0.1mm in diameter, in sphene and hornblende.

Actinolite, chlorite, and sericitized plagioclase surrounded by biotite form calc-silicate layers 2 to 10cm thick within the amphibolite. These assemblages pinch and swell along strike causing a discontinuous layer. A 1 meter-thick marble with distinct bedding also occurs within the amphibolite. It is essentially pure calcite.

Petrographic studies found no facies-diagnostic metamorphic mineral assemblages. Hornblende-diopside-plagioclase merely indicate a metamorphic grade in the amphibolite facies (Hyndman, 1972, p. 354) or medium to high grade (Winkler, 1976, p. 82). The unit's structural position suggests the grade may be lower than sillimanite zone, probably placing it in either the kyanite or staurolite zone of the amphibolite facies (Winkler's medium grade).

### Eastern Quartzite

White to slightly rust-colored quartzite comprises greater than 90% of this unit. Quartz-rich schists, mica schists, and calc-silicate beds interlayered with the quartzite make up the remaining 10%. Contacts between all rock types tend to be gradational. The quartzite occurs both as massive layers and as beds 2 to 4 cm-thick in a section some tens of meters thick. Micaceous partings accentuate the bedding, and also make nice planes along which local quarriers split the decorative rock. The other interlayered rock types vary in thickness from 0.5 to 3.0 meters, averaging 1 meter. They combine to form thicknesses of 3-5 meters. In outcrop, this unit forms stepped cliffs as it spalls off along joints and bedding planes. Two small quarries improve exposure. To maintain terminology consistent with Cheney's (in press), this unit is here called the Eastern Quartzite, as opposed to the Kifer Quartzite (Donnelly, 1978).

In thin section, the quartzite averages 95% quartz, 5% muscovite, and a trace of pyrite. The 0.2 to 0.5mm-long anhedral quartz grains show sutured grain boundaries and undulose extinction. They are generally elongate parallel to the foliation.

Muscovite has two habits. Well aligned subhedral to anhedral laths 0.05 to 0.1mm long occur throughout the rock both between quartz grains, and partially enclosed within two quartz grains. They have straight cleavage planes, and show no signs of physical distortion. Coarser muscovite grains from 2 to 5mm long occurring in thin laminae 2-3mm thick have bent and broken cleavage planes, and splayed ends. Quartz grains nearby are fine-grained and extremely sutured and granulated, evidently reflecting locally concentrated cataclastic deformation.

As the thickness of these muscovite laminae increase, the quartzite grades into quartz-mica schist with up to 40% muscovite. Coarse muscovite, similar in habit and size to the above muscovite, still shows deformation characteristics. Flaser textures appear, with quartz eyes surrounded by finer quartz grains. The quartz eyes show undulose and internally discontinuous extinction. The cataclastic foliation intersects the fine-grained well oriented muscovite at a small angle.

Tremolite, diopside, and minor fine grained plagioclase constitute the calc-silicate mineralogy. They form thin compositional layers in the quartz-mica schists.

The only evidence of metamorphic grade within the unit is the assemblage of diopside-tremolite-plagioclase which indicates metamorphic conditions within the amphibolite facies.

#### Summary of Metamorphic Grades

In the structurally lowest metamorphic unit, the equilibrium assemblages of sillimanite-orthoclase-almandine and orthoclase-almandine-biotite indicate

metamorphism within high grade, or sillimanite-orthoclase zone of the amphibolite facies. This unit entered this grade of metamorphism by the reaction: muscovite + quartzite  $\rightarrow$  sillimanite + orthoclase +  $H_2O$ , that occurred during shearing.

Those high grade assemblages do not exist in the overlying biotite plagioclase gneiss. Since shearing possibly drove the metamorphic reactions to a higher grade in the unit below, similar assemblages would be expected in this more pervasively sheared unit if conditions had been appropriate. Instead, the assemblage biotite-muscovite-orthoclase occurs throughout, indicating medium grade metamorphism. The change in metamorphic conditions associated with the shearing was not great enough to change the metamorphic grade in the biotite-plagioclase gneiss. Somewhere near the gneiss-quartzite contact lies the isograd separating high from medium metamorphic grade.

In the overlying amphibolite, hornblende-diopside-plagioclase form an equilibrium assemblage. A calc-silicate equilibrium assemblage of plagioclase-diopside-actinolite occurs in the upper quartzite. The assemblages in the upper three metamorphic units may form in either the staurolite or kyanite zone. As all rocks in the study area display Barrovian assemblages, a "normal" geothermal gradient of approximately  $25^{\circ}C/km$  may be assumed. Over this exposed stratigraphic thickness of less than 1.5 km, the temperature should change a maximum of  $40^{\circ}C$ . As this is probably not great enough to change metamorphic zones, the entire sequence above the bottom quartzite should fall in the kyanite zone of the amphibolite facies.

### Stratigraphic Relationships

The quartzite unit with its associated marbles, calc-silicate layers and pelitic schists forms the stratigraphically and structurally lowest unit in the study area. It was obviously a sedimentary sequence prior to metamorphism.

The biotite-plagioclase gneiss lies unconformably above it. The basal portion of the gneiss truncates bedding of the quartzite. It also contains inclusions of the underlying rock unit in this area and in others (Cheney, in press). These relationships, and the unit's massive appearance and uniform composition combine to strongly suggest an igneous granodiorite intrusion as a protolith. Subsequent metamorphism and shearing produced its foliation.

The amphibolite overlies the gneiss everywhere in the Nancy Creek area. The contact appears to be locally conformable. Where exposed, it forms a sharp, slightly undulating surface. No contact effects of any kind were found. No dikes or apophyses of the gneiss cut the amphibolite, and the gneiss contains no amphibolite inclusions. Regionally, the amphibolite occurs only along parts of the eastern margin of the Kettle Dome, suggesting an unconformity along at least one of its contacts.

Preto (1970) claims that para- and ortho-amphibolites become chemically, and consequently mineralogically, indistinguishable after metamorphism and metasomatism affect them. Both of these processes have altered the Nancy Creek amphibolites. The mineral percentages of these amphibolites may come from the metamorphism of either an andesitic rock, or a shale



containing up to 35% free carbonate (Nockolds, 1954). Field relationships must decide their origin. Conformable calc-silicate and marble layers are described in this thesis and by Donnelly (1978). Lyons (1967) notes gradational contacts between correlative amphibolites and the surrounding meta-sedimentary rocks. Though not conclusive, these imply a sedimentary origin. This origin also better explains the unit's thickness and lack of regional extent.

The eastern quartzite also appears locally conformable, as it consistently sits above the amphibolite. Regionally, however, it lies in contact with both the amphibolite and the biotite-plagioclase gneiss, cutting across their contacts undeflected (Fig. 2). This indicates an erosional unconformity rather than an intrusive contact at the base of the eastern quartzite. This unconformity may explain the regionally unconformable outcrop pattern of the amphibolite. The lack of intrusive relationships between the amphibolite and underlying gneiss may suggest the presence of an erosional unconformity there also.

#### Correlation and Age of the Metamorphic Stratigraphy

Parker and Calkins (1964), working west of the northwest corner of the Kettle Dome, describe a 17,000-foot thick metamorphic section, naming it the Tenas Mary Creek Group (TMC). It consists of seven units, from top to bottom:

1. Phyllite unit
2. Schist unit
3. Quartz-plagioclase gneiss
4. Hornblende schist

5. Quartzite
6. Marble and related rocks
7. Orthoclase-quartz-oligoclase gneiss.

An unconformity exists between the phyllite and schist units, and another one possibly between the schist unit and quartz-plagioclase gneiss. Metamorphic grade decreases continuously from upper amphibolite grade in the basal unit to greenschist in the phyllite.

Cheney (1979) extended the TMC units to the Kettle Dome, noting the same section throughout the area. He excluded the phyllite unit due to its low metamorphic grade and underlying unconformity. The described section at Nancy Creek correlates with the upper part of the TMC type section. The lower quartzite unit correlates with the TMC quartzite. The biotite-plagioclase gneiss matches their quartz-plagioclase gneiss. The intervening hornblende schist in the type section thins to the east (Parker & Calkins, 1964) and does not appear on the eastern edge of the dome. The upper schist unit also is missing. The eastern quartzite, and the amphibolite crop out only on the eastern edge of the Kettle Dome. Donnelly (1978) included them in the TMC section as they contain the same generation folds. There is also no sharp change of metamorphic grade from underlying rocks.

Parker and Calkins (1964) claim a pre-Permian age for the TMC rocks, because Permian greenstones overlie them. They correlated the TMC rocks with the Grand Forks Group to the north (Little, 1954; Preto, 1970), noting many similarities between TMC and Shuswap terrane rocks. Little (1957) dates the Grand Forks Group as pre-Pennsylvanian, and probably

Precambrian. Wanless and Reesor (1975) provide isotopic evidence of Proterozoic basement rock involvement in the Mesozoic structures of the Shuswap terrane, using a Pb-U age determination on a zircon separate from a granodiorite gneiss of the core zone of the Thor-Odin gneiss dome of  $1960 \pm 45$  m.y.

Interpreting the shear zone that forms the eastern border of the Kettle Dome as a detachment (Cheney, 1979), Bowman's (1950) Paleozoic units east of the Kettle River in the Orient area just north of Nancy Creek would have overlain the TMC metamorphic section. His basal Paleozoic unit, the Glasgow marble, correlates with the Cambrian Metaline Formation (Yates, 1971). This necessitates either a Cambrian or Precambrian age for the metamorphic rocks. Preliminary Rb/Sr whole rock dates of 600 to 1200 m.y. from R. L. Armstrong (1977, personal communication in Cheney, in press) on the biotite-plagioclase gneiss and underlying granitic gneiss (GPPG in Fig. 2) (Cheney, in press) indicate a Precambrian and possibly pre-Beltian age for the TMC section.

The TMC section does not correlate well with either the basal Cambrian, Beltian, or Windermere-Deer Trail sediments in adjacent areas of northeastern Washington (Cheney, 1979; Miller and Clark, 1975; Griggs, 1973; Yates, 1971). These sedimentary rocks have much lower metamorphic grades, and Cheney (1979) could find no common protoliths for the TMC marbles, or quartzites with the appropriate composition or thickness.

Miller and Clark (1975) mention a belt of highly recrystallized quartzite, amphibolite, and quartz-mica schists in the Chewelah-Loon Lake area, southeast of Nancy Creek. These rocks are in contact for several miles with the basal Beltian unit, the Pritchard Formation. Poor exposure prohibited defining any contact relationships, yet they could not reliably assign the metamorphic rocks to the Pritchard or any other mapped unit. Griggs (1973) mapped mica schists, quartz-plagioclase-biotite gneiss, quartzite, migmatites, and porphyroblastic gneiss with shearing and mylonitic zones roughly parallel to the foliation. He claims they are Beltian sediments, despite their difference in grade (sillimanite and greenschist facies), a lack of rocks with intervening metamorphic grades, and no lithologic correlations despite close spatial relationships. Both of the areas of metamorphic rocks described belong to the Spokane Dome, an area of gently folded, high grade metamorphic rocks. As noted, these rocks do not lithologically correlate with Beltian strata, and Cheney (in press) noticed that on a regional scale, Beltian sediments conformably surround this dome. This strongly suggests a pre-Beltian age for its rocks. The rocks of the Kettle Dome correlate well with the Spokane Dome lithologically and with its metamorphic grade, implying a pre-Beltian age for them also.

## CHAPTER III

### GRANITE DIKES

#### Introduction

Granite masses of the Nancy Creek area come in many sizes, shapes, and textures. Their size varies from veinlets 1 cm thick and 10 cm long, to masses 10 meters thick and greater than 100 meters long. They may form ameoboid pods, or tabular bodies. Their textures display grain sizes from very fine to very coarse, though they generally fall into three size categories: aplitic, granitic, and pegmatitic. The aplitic variety has a grain size of 0.2 to 0.5mm, and a sugary texture. The granitic dikes have equigranular grains 1-3mm in diameter, and look like a typical phaneritic granite. The grain size of the pegmatite varies from 5 to 20mm. One texture commonly grades into another over a short distance of 1-2cm.

Despite the great dimensional and textural variety, the mineralogy remains consistent and the compositions remain within limited bounds. Although individual hand samples and zones in the dikes may range in composition from granite to syenite in composition, they average out to a granite. They are typically leucocratic with major mineral percentages of 45% orthoclase, 30% quartz, and 20% plagioclase. Biotite, garnet, and muscovite amount to 5%, except for local concentrations. Apatite, zircon, magnetite, and pyrite generally comprise less than a percent.

### Petrography of Pegmatite Dikes

The pegmatite dikes have a consistent leucocratic mineralogy of quartz, orthoclase, and plagioclase, averaging 30%, 45%, and 25% respectively. Zoning within the dikes provides different percentages as orthoclase ranges from 30 and 80%, quartz from 10 and 40%, and plagioclase from 5 to 45%. Despite the variations, an integrated composition still falls close to the average and, in all cases, in the granite range.

Orthoclase forms perthitic, anhedral grains 3 to 30mm in diameter. The coarser crystals occur as either porphyroblasts or augen, whereas the smaller 3 to 4mm crystals form lensoid stringers. The coarse porphyroblasts are generally poikilitic around their margins, containing inclusions of quartz, plagioclase, garnet and rarely muscovite. Myrmekitic and micrographic textures also occur as inclusions and along the edges of the large crystals. These poikilitic margins are optically clearer and show markedly less undulose extinction than the cores.

The common plagioclase is oligoclase,  $An_{20}$ . Its anorthite percentage varies from a rare low of 7 to a high of 25. The oligoclase characteristically occurs as anhedral to subhedral porphyroblasts or augen 2-10mm in diameter, and rarely as 0.2 to 0.6mm across, euhedral to anhedral inclusions in orthoclase. Along its borders it may contain minor quartz and orthoclase inclusions, and exhibit normal zoning. It generally shows minor sericite alteration.

Quartz occurs rarely as coarse "pegmatitic" crystals and generally in either interstitial aggregates of crystals 0.3 to 1mm in diameter or as 0.5 to 5mm thick lens-shaped stringers along foliation planes. Quartz crystals invariably have sutured grain boundaries and undulose extinction. The quartz stringers display internally discontinuous extinction.

Almost all granite dikes contain garnet in small amounts, especially the pegmatitic and aplitic dikes in which it averages 1-2%. In pegmatite dikes, it may comprise up to 25% when concentrated in planar and pod-like zones. It forms crystals which are 0.4mm to 1cm in diameter, subhedral to euhedral, and generally cracked or broken. They are commonly poikilitic with apatite, quartz, and rare uraninite inclusions. Minor chlorite alteration appears along the cracked surfaces. In the pegmatites, and to a lesser extent in the aplites, garnet forms the main, if not only, ferromagnesium mineral. Where present, biotite is clearly subordinate. In the granitic dikes, biotite becomes dominant, with garnet in the subordinate role. This relationship, the occurrence, and the red color, suggest the garnets are pyrope-almandine.

Biotite and muscovite, typically common granitic minerals, are uncommon in these dikes. Biotite occurs in approximately a quarter of the pegmatite dikes, and ranges from 0 to a maximum of 2% in uncontaminated dikes. It forms small laths 0.1 to 0.6mm long, generally found only in cataclastic zones. These laths show no deformation of either crystal shape or cleavage planes. The appearance of biotite commonly coincides

with a decrease in the garnet percentage. Muscovite is less common than biotite, appearing in fewer than 10% of the dikes. It may occur as unoriented flakes up to 0.6mm long, but characteristically mimics biotite in the cataclastic zones.

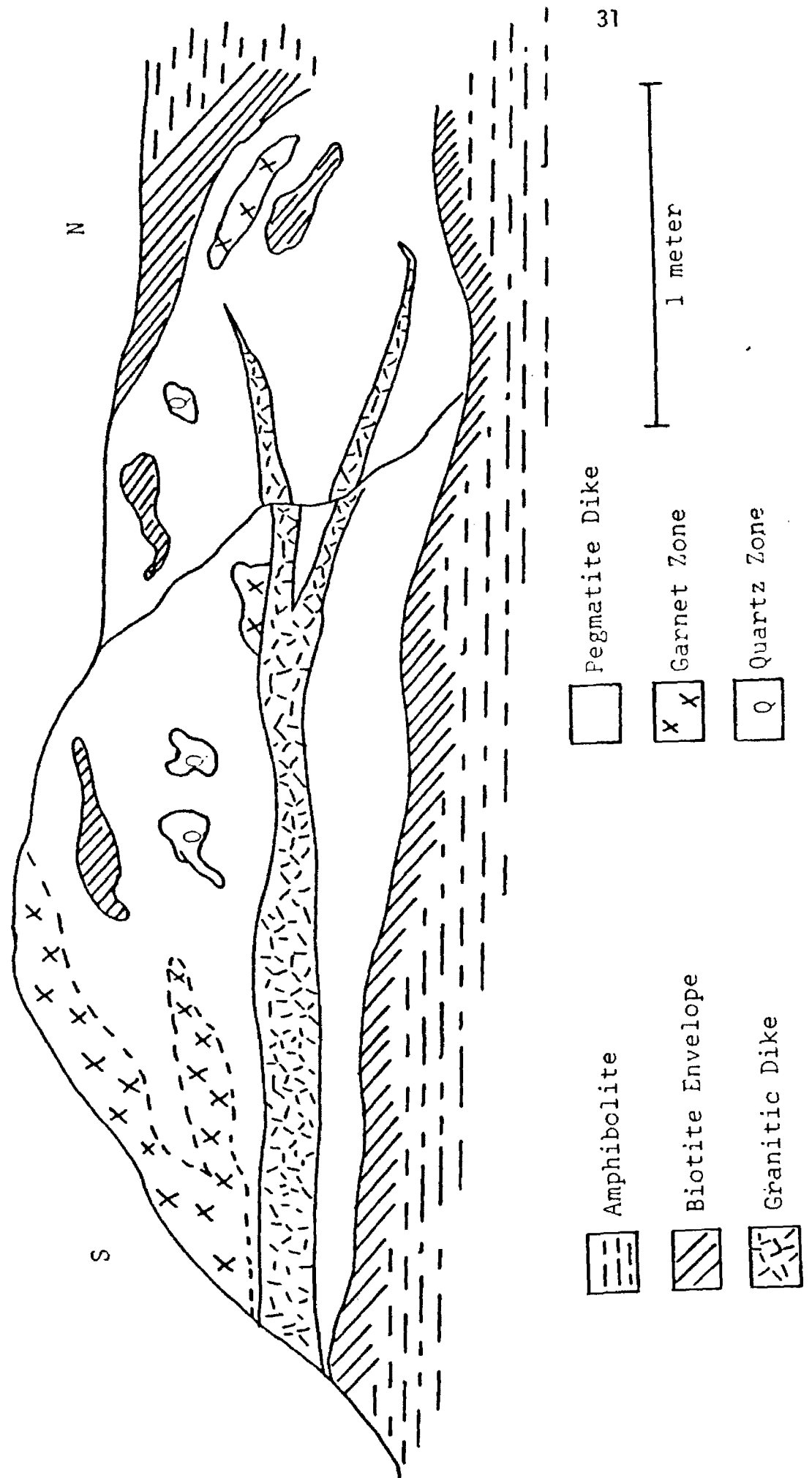
Of the trace minerals present, apatite appears in greatest abundance. It forms cracked subhedral to euhedral hexagonal prisms 0.2 to 0.4mm in diameter and up to 1mm long. They generally amount to much less than a percent except where in local concentrations of up to 2-4%, associated with garnet concentrations. The remainder of the trace mineral suite consists of pyrite, magnetite, zircon, and sphene. Zircon and sphene occur rarely. Pyrite and magnetite are more common, and may show minor concentrations with uraninite in the garnet-rich zones.

Mineralogic zoning. No systematic mineralogic zoning, such as the classic concentric zoning of many pegmatites, occurs in this pegmatite system. Some zoning does occur, forming lensoid layers parallel to the long axis of the dikes, and small pods, both in irregular patterns generally truncated by later dikes (Fig. 4).

Layers of conspicuous garnet concentration form the most noticeable zones. Apatite, pyrite and/or magnetite, uraninite, and well developed pegmatite texture accompany the garnet which forms up to 25%. No systematic variation in the major minerals occurs with these zones. Pods of pure quartz occupy the central portion of a few dikes, possibly representing a late stage zone analogous to the classic quartz core in well-developed zoning patterns.



Figure 4: Sketch of a Uraniferous Pegmatite Dike



The pegmatites also contain poorly developed cryptic zoning, based on changes in plagioclase content to a more albite-rich plagioclase, or changes in the plagioclase:orthoclase ratio. These zones have irregular patterns commonly truncated by later dike phases. How they formed is unclear, although they may represent incomplete differentiation trends.

Crystallization paths. The ever-present cataclastic textures (discussed later) conceal many primary relationships between minerals, making crystallization paths difficult to determine. The interstitial habit and paucity of coarse porphyroblasts of quartz indicates it crystallized late. The coarse habits of orthoclase and plagioclase imply they began to crystallize early. The poikilitic margins of both feldspars that engulf earlier grains show they also grew late. The sharp line between the core and outer zone of plagioclase porphyroblasts and different optical properties suggest this growth was episodic, not continuous.

Plotting the granite composition in a An-Ab-Or-Qz tetrahedron (Fig. 5), it falls on, or very close to, a cotectic surface. On the surface, orthoclase and plagioclase are in equilibrium with a melt and vapor. With cooling, those two minerals crystallize, until the melt composition reaches the cotectic line (P-E5). Now quartz crystallizes along with orthoclase and plagioclase. As the melt moves toward P, the Ab content of the plagioclase increases. Thus experimental predictions match the proposed crystallization path deduced from textures. The orthoclase and episodic plagioclase overgrowths, and myrmekitic and



micrographic textures along their margins may be caused by simultaneous crystallization of crushed quartz and feldspar following cataclasis (Spry, 1969, p. 104).

### Granitic and Aplitic Dikes

The mineral composition of these textural types of dikes very closely resembles the pegmatite dikes. They contain 35-40% orthoclase, 30-35% quartz, and 20-35% oligoclase ( $An_{17-20}$ ), differing from the pegmatites only in a small decrease in orthoclase. They differ texturally in their finer grain size and a lack of coarse porphyroblasts. These finer grained dikes are equigranular except where altered by cataclasis. The grain size of the aplites is 0.2 to 0.5mm in diameter, and that of granitic dikes is 1-3mm in diameter. The slightly perthitic orthoclase with poikilitic edges resembles the orthoclase in the pegmatites. Myrmekite and micrographic textures occur along its edges. Plagioclase also resembles its pegmatitic counterpart with uniform cores and normal zoning along its margins. Quartz forms interstitial grains and stringers along cataclastic foliation. It shows undulose extinction and sutured grain boundaries.

Granitic dikes contain 1-5% biotite and traces of garnet. Biotite occurs along shear zones and in schlieren as 0.2 to 0.4mm-long subhedral to euhedral crystals commonly undeformed by the cataclasis. Aplite dikes tend to contain more garnet than biotite, the total percentage of the two remaining the same as in the granitic dikes. The garnet forms unbroken, euhedral crystals within the shear zones.

Muscovite is more abundant in the aplitic and granitic dikes than in the pegmatites, and has two populations. Anhedral to subhedral coarse-grained muscovite 1-3mm long occurs in 1-2mm-thick layers. The crystals are deformed, with bent and broken cleavage planes. The second population of well oriented undeformed, 0.3 to 0.8mm long flakes mimic biotite in the shear zones. Apatite and magnetite are randomly distributed in trace amounts, together totalling less than a percent of the rock.

Cataclastic textures are prevalent, but differ from those in the pegmatites due to original grain size differences. Quartz grains have sutured grain boundaries and undulose extinction. Feldspars display bent cleavage planes and optically discontinuous extinction. Cataclasis has broken crystals into parallel zones of fragments 0.1 to 0.5mm in diameter. Flaser textures are uncommon because of the lack of porphyroblasts in the original rock. Mylonitic textures do occur locally.

Unlike the pegmatites, these two types of dikes present neither zoning of any kind nor concentrations of either garnets, apatite, or magnetite. The dikes have a uniform composition across their width, with a random distribution of accessory minerals.

In summary, the pegmatitic, aplitic and granitic dikes are virtually identical in composition and major mineralogy. Biotite in the granitic dikes, as opposed to garnet in the other two, and the lack of muscovite in the pegmatites comprise the only real mineralogic differences. Texturally, the three types of dikes differ in grain size, and in the

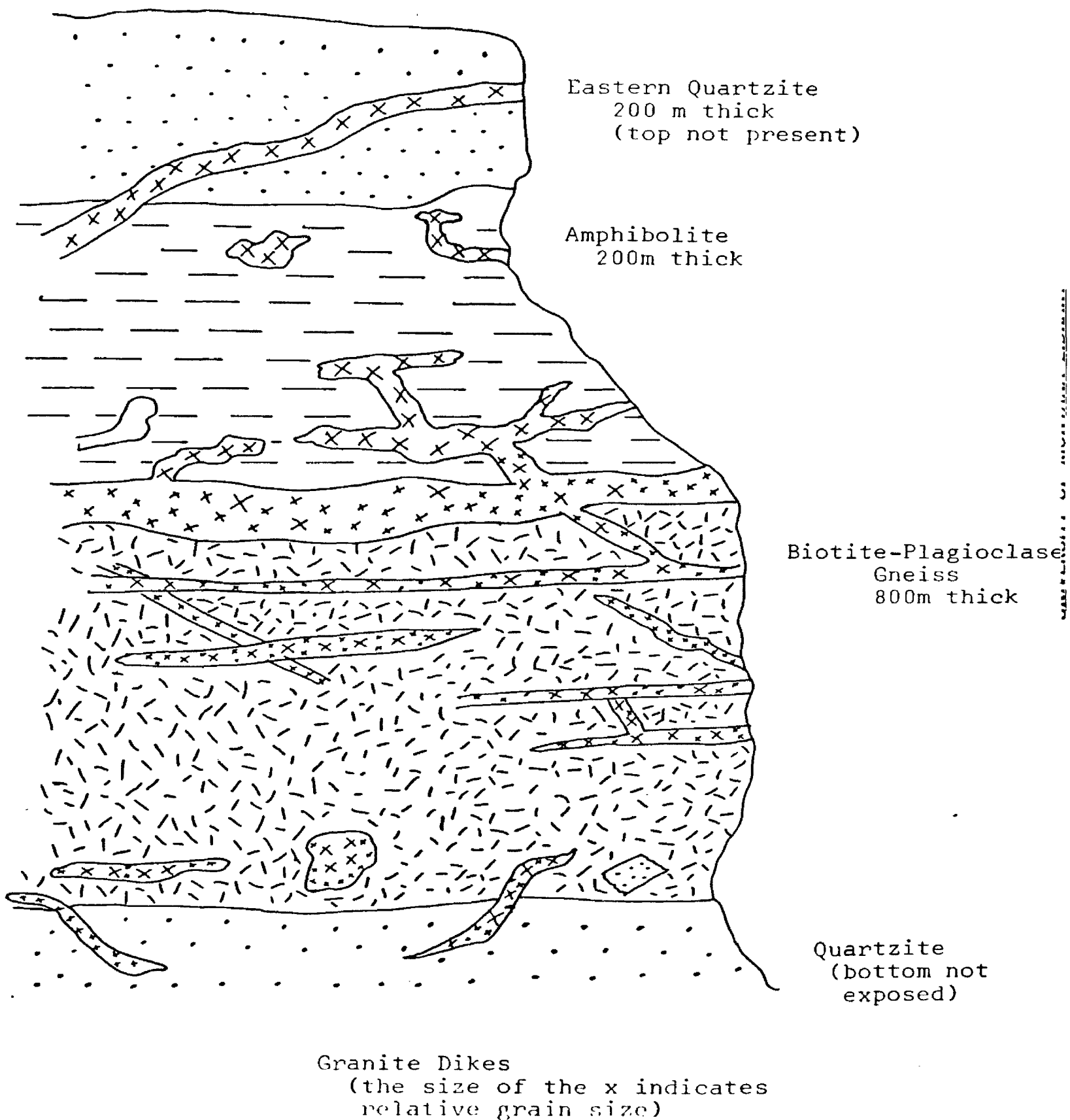
way those grain sizes reacted to cataclasis. More importantly, only in the pegmatites do any zoning and trace mineral concentrations occur.

### Stratigraphic Distribution of the Dikes

As the youngest rock type, the granite dikes cut across every metamorphic unit. They are not evenly distributed, but show definite concentrations in different rock types, being most abundant in the biotite-plagioclase gneiss and the amphibolite. Within these two rock units, two zones of heavy concentration occur: 1) near the gneiss - amphibolite contact, and 2) just below the amphibolite - Eastern Quartzite contact Fig. 6). The geometric form of the dikes also varies with rock type, controlled primarily by the differing reactions of the rock units to the shearing event.

Dikes in the biotite-plagioclase gneiss. Excluding the top 10 meters of this gneiss, the dikes show a reasonably even distribution of dikes with their number decreasing slightly with depth. They constitute approximately 5% of the volume of the gneiss, with local concentrations reaching 15-20%. They generally form tabular dikes that either parallel the foliation, or cut it at a high angle. Pod-shaped masses occur in the lower part of this unit where the shear foliation is not as pronounced. Near the top of the unit where shearing intensity was greater, dikes that parallel the foliation dominate. In this orientation, they may maintain a constant thickness for greater than 100 meters. The distribution of the different forms strongly implies a control on emplacement imposed by the shear foliation.

Figure 6. Generalized Diagrammatic Cross Section  
(not to scale)



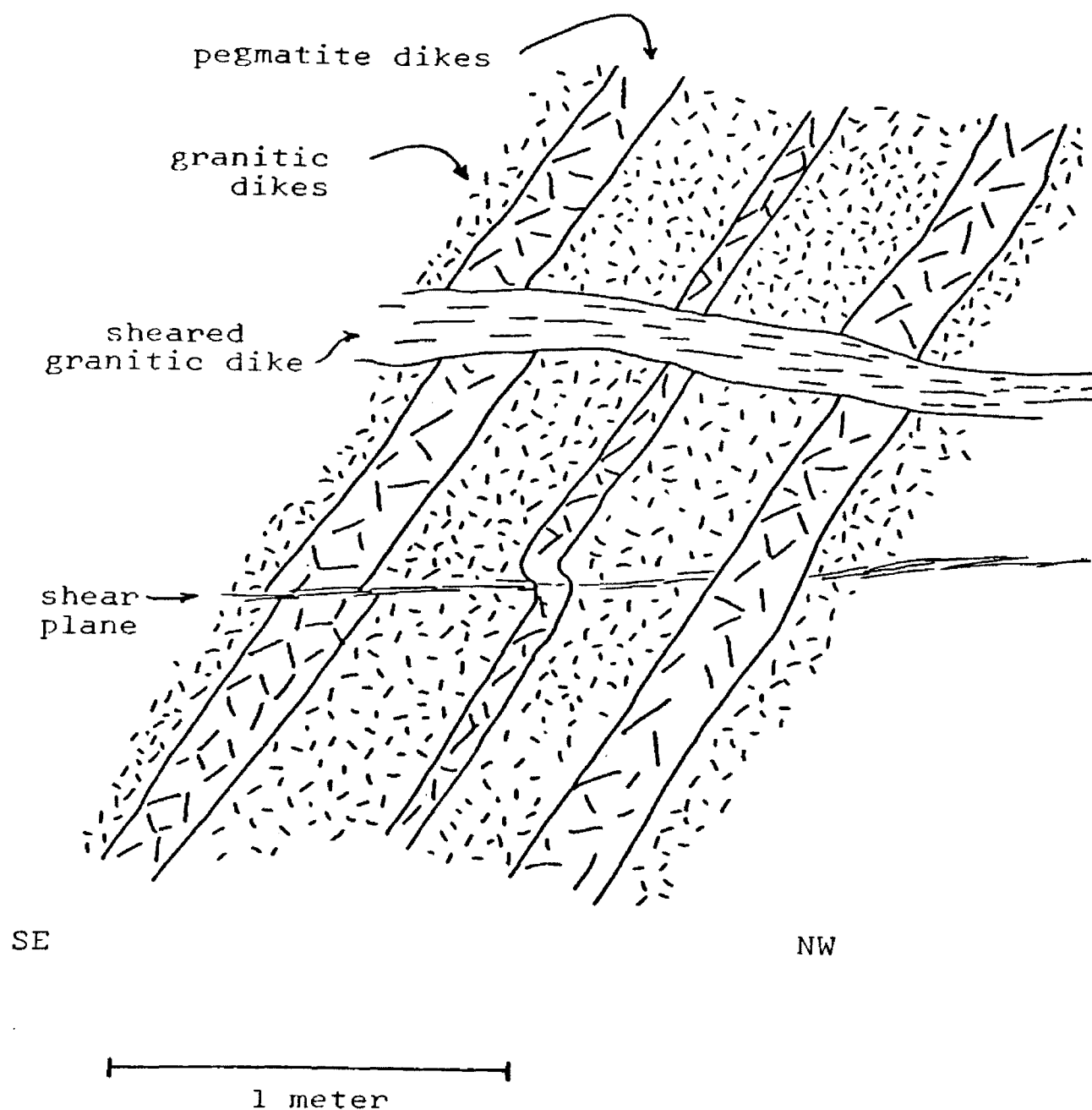
The dikes average a meter in thickness, and generally have sharp boundaries with the gneiss. Granitic textured material 2-10cm thick forms an outer shell that grades quickly into a coarse, more pegmatitic core. This outer shell may be absent, or conversely, the pegmatitic core may be absent. No mineralogic zoning is present.

Where the outer shell is present, contact effects on the country rock are minimal. Where it is absent, 2-4cm thick apophyses of pegmatitic orthoclase, quartz, and minor plagioclase invade the gneiss parallel to its foliation. They may extend for 3-4 meters before thinning to a row of almost unconnected porphyroblasts and pinching out. This extent and lack of a chill zone implies a fluid of low viscosity with a small temperature gradient between it and the country rock.

The dikes show various relationships to the shear foliation in the biotite-plagioclase gneiss. The shearing has affected some intensely, and others only a little. One outcrop shows a series of three parallel pegmatite dikes separated by granitic material, and lying at a high angle to the shear foliation. A shear zone offsets one dike, bends another, and has no effect on the third (Fig. 7). This conclusively shows these dikes formed concurrent with the shearing event. All dikes show some evidence of cataclasis, so intrusion of the dikes ended before the shearing did. It also shows they formed over a period of time, and did not intrude the metamorphic rocks in one big magmatic pulse. Granitic and pegmatitic varieties alternate, possible due to changing water pressure relative to the confining pressure. Previously established fluid pathways were used several times.



Figure 7. Sketch of contiguous pegmatite dikes with differing relationships to a shear plane.  
Location: NW corner, Sec. 6, T36N, R37E



Three shear zones offset another pegmatite which is surrounded by granitic material (Fig. 8). Displacement of the pegmatite shows that the stratigraphically higher parts moved east relative to the lower rock.

Dikes at the gneiss-amphibolite contact. In the upper 10 m of the biotite-plagioclase gneiss, the concentration of dikes parallel to the foliation increases to 20-25% of the section. Overlying this, at the gneiss-amphibolite contact, a 10 m-thick dike section commonly separates the two units. Granitic texture dominates, but lenses of pegmatitic textures less than 10 cm thick and a meter long commonly occur. Ubiquitous cataclastic textures vary from very common flaser texture to 2-5cm thick mylonite zones. This granitic mass may contain 1-2m-long blocks of amphibolite.

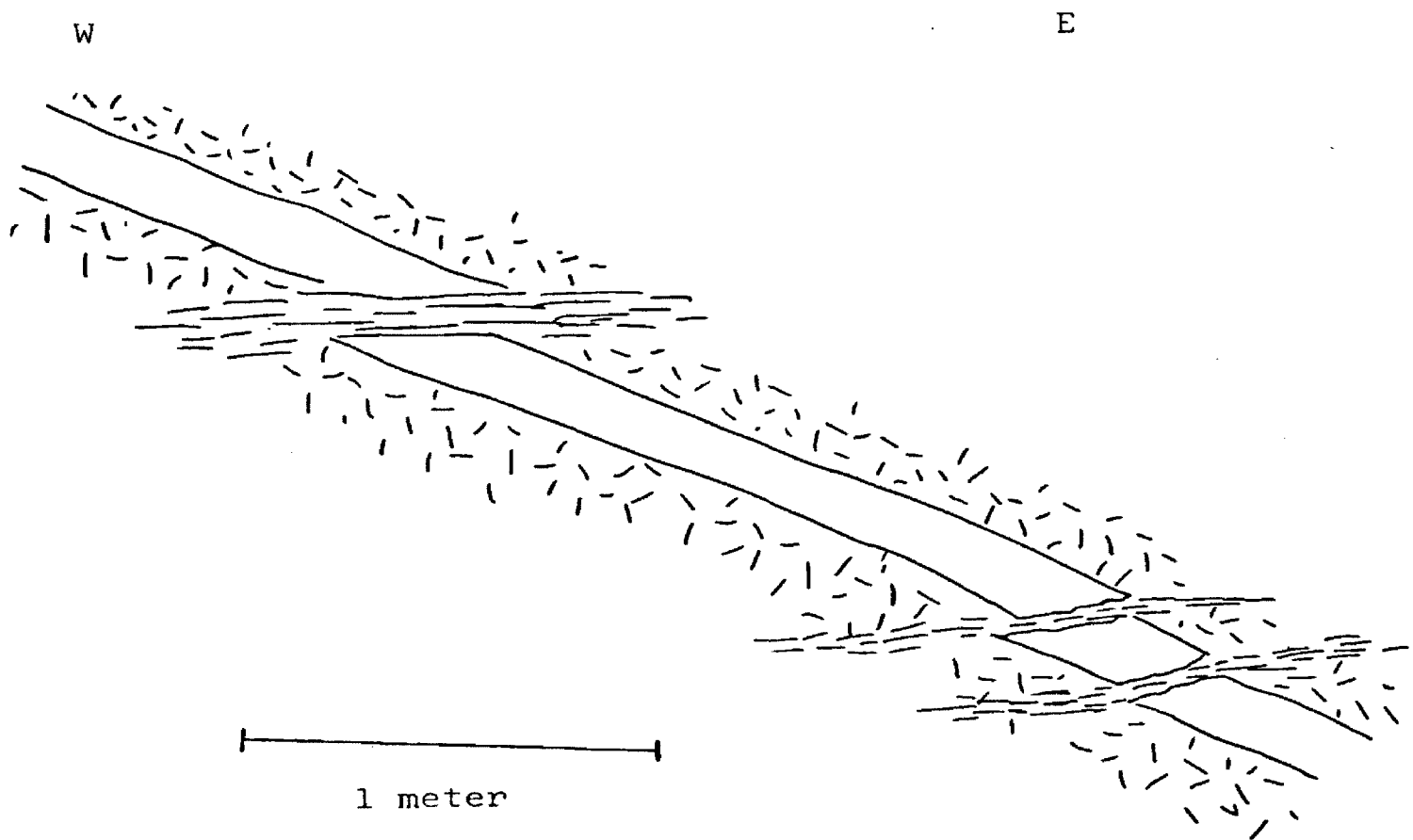
Dikes in the amphibolite. Dikes in this unit concentrate in two areas: its bottom 30 meters, and top 10 meters. In most of the amphibolite section, the dikes amount to less than 10% of the rock. In these areas of high concentration, they constitute up to 40 and 50%. They engulf blocks of the amphibolite which now show a rotated foliation not consistent with either regional metamorphic or cataclastic trends. These blocks contain few shearing effects while the engulfing material shows prevalent shear textures.

The dikes undergo some very distinct changes upon entering the amphibolite. The characteristics of their shapes, textures and contact effects vary a great deal. In the biotite-plagioclase gneiss, the dikes form tabular bodies with straight, sharp contacts, and constant thicknesses. They all either parallel the foliation or cut it at a high angle.

Figure 8

Displaced pegmatite dike showing relative movement on shear planes.

Location: SE corner, SW/4, Sec. 30, T37N, R37E



This gives the impression of rigid controls imposed by the country rock. In the amphibolite, a greater variety of shapes and sizes exist. Tabular sheets still dominate, but they pinch and swell, change orientations, cut the foliation at all angles, transect other dikes, and branch out, forming an anastomosing pattern. Pods and other irregular shapes separate blocks of amphibolite. The strict control of orientation and shape so prevalent in the gneiss does not appear here.

Simple dikes cored by pegmatitic textures and bordered by granitic texture are still the most common type, constituting 60% of the dikes. They average 1 to 1.5 meters thick, and typically form tabular dikes with varying thickness. They have contact aureoles up to 1.5cm thick, where biotite rims hornblende and plagioclase has more sodic margins. Dikes containing only fine grained material comprise 20% of the dikes. They tend to be thin, less than .3 meters thick, have sharp contacts, and minimal contact effects.

In twenty percent of the dikes, pegmatitic textures dominate, whereas granitic textures are limited to dikelets that cut the pegmatite, or to zones within the pegmatite body. A fine grained chill zone may be found along the basal contact but generally is lacking. A biotite envelope 2cm to a meter thick occurs along the remaining contact. This textural dike type forms the tabular bodies with the greatest variations in thickness, and most of the pod- or irregularly-shaped bodies.

Mineralogic zoning occurs only within these pegmatites in the amphibolite. The most noticeable garnet-apatite-magnetite-uraninite-zones tend to form near the tops of dikes. Central patches of quartz rarely

occur. Aplitic and granitic textures cross the pegmatites randomly. A well developed biotite envelope accompanies any pegmatite with zoning. In most of these pegmatites, later contemporaneous dikes or dike phases truncate the poorly developed zones, indicating a system open to the influx of more magma. This influx of material would disrupt most zoning and differentiation processes.

The pegmatite fluids reacted with the amphibolite to form the biotite-rich envelope surrounding many pegmatites. This zone varies from being a modest contact zone 1-2cm thick, to a well-developed sheath 1 meter thick. With well-developed envelopes, biotite occurs as stringers and pods within the edges of the pegmatite. These biotite concentrations form unoriented swirls that wind between coarse feldspars. These swirls grade outward into massive biotite with both veinlets, and isolated grains of feldspar. The biotite shows a poor preferred orientation roughly parallel to the edges of the dikes. It is coarse-grained, up to 1cm in diameter, and generally poikilitic with magnetite, apatite, and sphene inclusions. It may bend around feldspar grains, showing the effect of a directed stress after it grew.

Two kinds of plagioclase and orthoclase occur within the envelope. Normally zoned plagioclase has a core of  $An_{40}$  remnant from the amphibolite, and a rim of  $An_{15-20}$ . The other plagioclase grains have a composition of  $An_{15}$ , with no core and little zoning. They grew directly from the pegmatite fluids, as did the orthoclase. All three feldspars are coarse grained, up to 3cm in diameter, and subhedral. They have

grown concurrently with the biotite. Isolated feldspars are surrounded by biotite, and have no direct connection with the dike.

Garnet commonly concentrates with the biotite in this envelope. Magnetite, pyrite, and apatite may accompany it. Only minor quartz is present.

Farther from the dike, the total replacement of hornblende by biotite becomes only biotite rimming the hornblende. With greater distance of a meter or more, this partial replacement occurs only along a few foliation planes in the amphibolite.

Dikes in the Eastern quartzite. Few dikes cut the Eastern quartzite. Considering the concentration of dikes just below this unit, it seems that the quartzite acted like a cap, sealing the pegmatites below. Those dikes that do across the quartzite are pegmatitic, and generally radioactively anomalous (2-5 x background). They form thin, tabular layers less than 1 meter-thick, nowhere pods, and generally intersect the foliation at a small angle. Exposure nowhere showed the dikes enclosed in anything but the essentially inert quartzite, and no contact effects were observed.

Dikes in the quartzite. Poor exposure limits a detailed description of dikes in this unit. Dikes of granitic texture, and pegmatitic cores bordered by granitic texture appear. They form tabular bodies 4cm to 1 m thick, both concordant and discordant to the layering. Mineral and chemical composition do not differ from previously described dikes.

### Cataclastic Textures in Pegmatitic Rocks

Broken, crushed or sheared zones appear in every thin section to some degree. The intensity of deformation varies from mere suturing of grain boundaries, through flaser textures to mylonite. In the mildly deformed varieties, cataclasis caused undulose extinction and sutured grain boundaries in quartz. As the intensity increases, thin parallel zones of broken crystals 1-2mm thick separate 1-2cm of unbroken crystals. With still greater intensity, these layers of broken crystals thicken, and coarse feldspar porphyroblasts become separated by their crushed margins. Flaser textures develop where the crushed material has so increased that the porphyroblasts swim in a sea of finely broken grains. They become slightly rounded, with bent cleavage and twin planes, and undulose extinction. Quartz forms stringers in the shear zones. Zones of mylonite 2-20 cm thick are interspersed with flaser textures where shearing was most intense. Crystals broken down to 0.05mm in diameter and streaked out quartz comprise these zones.

Biotite and muscovite developed along some shear planes. They occur as 0.1 to 0.3mm-long, subhedral to euhedral flakes, with absolutely straight cleavage planes and no splintering of their ends. They evidently grew after the shearing.

The intensity of shearing varies in a regular fashion depending on the stratigraphic location and orientation of the dike. Granite dikes separating the biotite-plagioclase gneiss from amphibolite display the most intense shearing. Somewhat less intense deformation appears in dikes paralleling the foliation in the top 30 meters of the biotite-plagioclase gneiss. Dikes in the amphibolite that parallel the foliation

and separate unsheared blocks of country rock display slightly less intense deformation. Vertical dikes in these same units show deformation characteristics of lower intensity than their horizontal counterparts except where the vertical dikes cross an intense shear zone. Shearing developed textures that form a consistent horizontal, planar foliation throughout the area.

#### Controls on Dike Distribution and Textures

The sizes, shapes, and textures of the granite dikes vary with the enclosing country rock. The physical response of different metamorphic rocks to shearing exerted great control over the pegmatite emplacement.

The structural analysis of Donnelly (1978) shows the biotite-plagioclase gneiss deforming ductilely during D-1. As D-1 wanes, the gneiss starts acting as a single 7-25 meter-thick component layer and cataclastic textures first develop. The dikes intrude the section along the structurally weakened shear zones between competent layers of this unit and were subsequently deformed. The internal competency of the gneiss helps explain both the constant thickness of the dikes over long strike lengths and the lack of penetration into the gneiss. Apophyses into the gneiss generally come from vertical dikes and then the apophyses follow shearing similar to that in the horizontal dikes. The parallel orientation of contiguous vertical dikes would result from competent blocks of gneiss repeatedly moving during the shearing and reopening pre-established magma pathways.



The amphibolite contains F-1 to F-4 structures in contrast to the gneiss which has only F-1 folds (Donnelly, 1978). Some blocks of amphibolite also have a primary metamorphic foliation rotated relative to the foliation of the gneiss. Both features necessitate relative movement between the two units, and therefore at least a minor detachment zone. This forms another structurally weakened area favorable for dike emplacement, as evidenced by the 10 meter thick granitic section there. Differential movement between the two units also created a zone of increased fracturing near the contact favorably preparing the rock for the concentration of dikes in the gneiss just below the contact, and in the amphibolite just above it.

Amphibolite reacted to the applied shear stress differently than the gneiss by breaking into a number of irregular blocks with foliation exerting only minor control on the fracturing. Continuing movement opened irregular fractures now filled by tabular dikes with varying thicknesses and irregular pods between blocks. These dikes, especially the pod-shaped ones, contain the best pegmatite textures, thickest biotite envelope, and the only zoning in the study area. The more brittle behavior, irregular fracturing, and continuing relative movement within the amphibolite attracted the more volatile rich magmas. The pegmatite pods show less shear effects, and were probably partly protected from it, or at least were not forming shear planes. This relative lack of disturbance allowed the minor zoning to develop.

The concentration of dikes at the top of the amphibolite resembles the concentration at its base suggesting similar reasons for, and controls,

on its emplacement. However, few dikes cross the contact into the quartzite. In thin section, quartz grains in the quartzite are smeared out, with elongate habits and sutured grain boundaries. Granulation and fracturing are not abundant, because annealing healed many of the cataclastic textures. This has apparently sealed off the quartzite as an escape route for the dike magma, keeping it below in the amphibolite.

### Timing of Dike Emplacement

Field relationships in the biotite-plagioclase gneiss demonstrate that the dikes intruded the metamorphic rocks during the shearing event. This cataclasis occurs as the last stage of D-1 deformation and just post-dates the metamorphic peak (Donnelly, 1978). As this stage of deformation correlates with gneiss dome emplacement, a drop in pressure should accompany its later stages.

### Consideration of Several Dike Systems

Dikes in the eastern quartzite and the amphibolite display good cross-cutting relationships with the enclosing country rock, chill zones at contacts, and contact metamorphism and metasomatism. These indicate that the dikes intruded the two metamorphic units. Identical mineralogy and composition, uranium occurrences, and physical continuity between some dikes in the different units shows they all belong to the same system. The same relationships hold for the dikes at the amphibolite-biotite-plagioclase gneiss contact, and for many dikes in the granitic gneiss. Thus a granite system exists that formed dikes with textures ranging from aplitic to pegmatitic.

Interpretation of the gneiss as a foliated intrusion raises the possibility that some of the dikes are magmatic differentiates of that intrusion. If stratigraphic relationships are interpreted correctly as showing an erosional unconformity between the gneiss and the quartzite, then dikes in the quartzite, and consequently the dikes in the amphibolite are related dikes in the granitic gneiss cannot have the gneiss as a magmatic source. As these dikes formed in the Eocene, they could not come from a Precambrian intrusion. Therefore, only some of the dikes in the gneiss could have differentiated from it. These differentiates would probably have the same gross mineralogy and textures as the Eocene dikes. They could also have a composition very similar to the later dikes, making the two sets of dikes indistinguishable.

Dikes that cut across the foliation, such as the three dikes with varying relationships to the shearing (Fig. 7), obviously formed from a later source. The same reasoning applies to dikes with an orientation controlled by the shear foliation. Shearing may have strung out earlier dikes along planes, causing this type of orientation. This process would produce extreme cataclastic textures in these dikes. As these textures are commonly lacking, this process can not generally apply.

All dikes in the eastern quartzite and the amphibolite, and most dikes in the gneiss, especially those near the upper contact of the gneiss where the strong control on orientation exists, comprise the later dike sets, and crystallized from a granitic system roughly contemporaneous with the formation of the Kettle Dome. A second earlier

dike set may exist that differentiated from the gneiss and is compositionally similar to the first set. As the later dike set constitutes the majority, and contains all uranium occurrences, all following discussions are restricted to it.

#### Types of Magma Present

Contacts, contact effects, and internal textures of the dikes require three types of magmas. Dikes with sharp contacts, phaneritic texture throughout, and little contact effect on the country rock crystallized from a viscous magma undersaturated with water (Jahns and Burnham, 1969). Dikes with phaneritic margins that show a sharp increase in grain size to a pegmatitic core began crystallization from a similar magma. Their sharp contacts, and little to no contact metamorphic and metasomatic effects indicate a magma of high viscosity and low volatile content. Crystallization of the anhydrous mineral assemblage concentrates the volatiles into the remaining melt. When the volatile content reaches the saturation point, an aqueous phase arises in equilibrium with the magma. Its principle effect is to promote the growth of large crystals and reactions between crystalline and fluid phases, rather than to introduce major changes in the sequence of minerals formation within the system (Jahns and Burnham, 1969, p. 858). Thus pegmatitic textures form in the core, and the order of mineral crystallization and composition remain constant. Potassium preferentially partitions into the aqueous phase over sodium and calcium, explaining why pegmatite systems contain slightly more orthoclase, and more abundant orthoclase overgrowths than granitic dikes.

Pegmatite dikes without the phaneritic margin, located mainly in the amphibolite, formed from magmas already saturated with water. They possibly bled off from partially crystallized magmas where the saturation point had been reached. As an aqueous phase already existed, they show markedly different contact effects with country rock. The lower overall viscosity results in more apophyses into both the amphibolite and the biotite-plagioclase granite. The aqueous phase interacted with the amphibolite, producing the biotite envelopes with orthoclase metacrysts.

The granite dikes originated from an undersaturated granite magma. Crystallization processes and possible differential removal of melts from partially crystallized dikes created saturated systems. This magma-aqueous phase system then produced pegmatite dikes, and metasomatic contact effects. The relative proportions of pegmatite dikes to the total number of dikes indicates to what percentage the original system was saturated with water at crystallization pressures. Visual estimates place the percentage at 70%.

## CHAPTER IV

### URANIUM

#### Description of Occurrences

In the Nancy Creek area, anomalous concentrations of uranium (anomalous means greater than three times background on a hand-held scintillometer) appear only in pegmatite dikes and their metasomatic halos. All metamorphic units, and the finer grained dikes display background radiation only. Analyses of representative rock samples show the metamorphics contain less than 2 ppm uranium and the barren dikes contain 5-10 ppm uranium. For a reference point, an average granite contains 3-5 ppm uranium. The great majority of pegmatites are also barren emitting gamma radiation of 25-50% higher than the finer grained dikes. Ten percent do show anomalous radioactivity corresponding to 10-50 ppm uranium, and less than two percent contain any concentrations in excess of 100 ppm. The amphibolite encloses all of these dikes except one which lies in the biotite-plagioclase gneiss 5 meters below the gneiss-amphibolite contact.

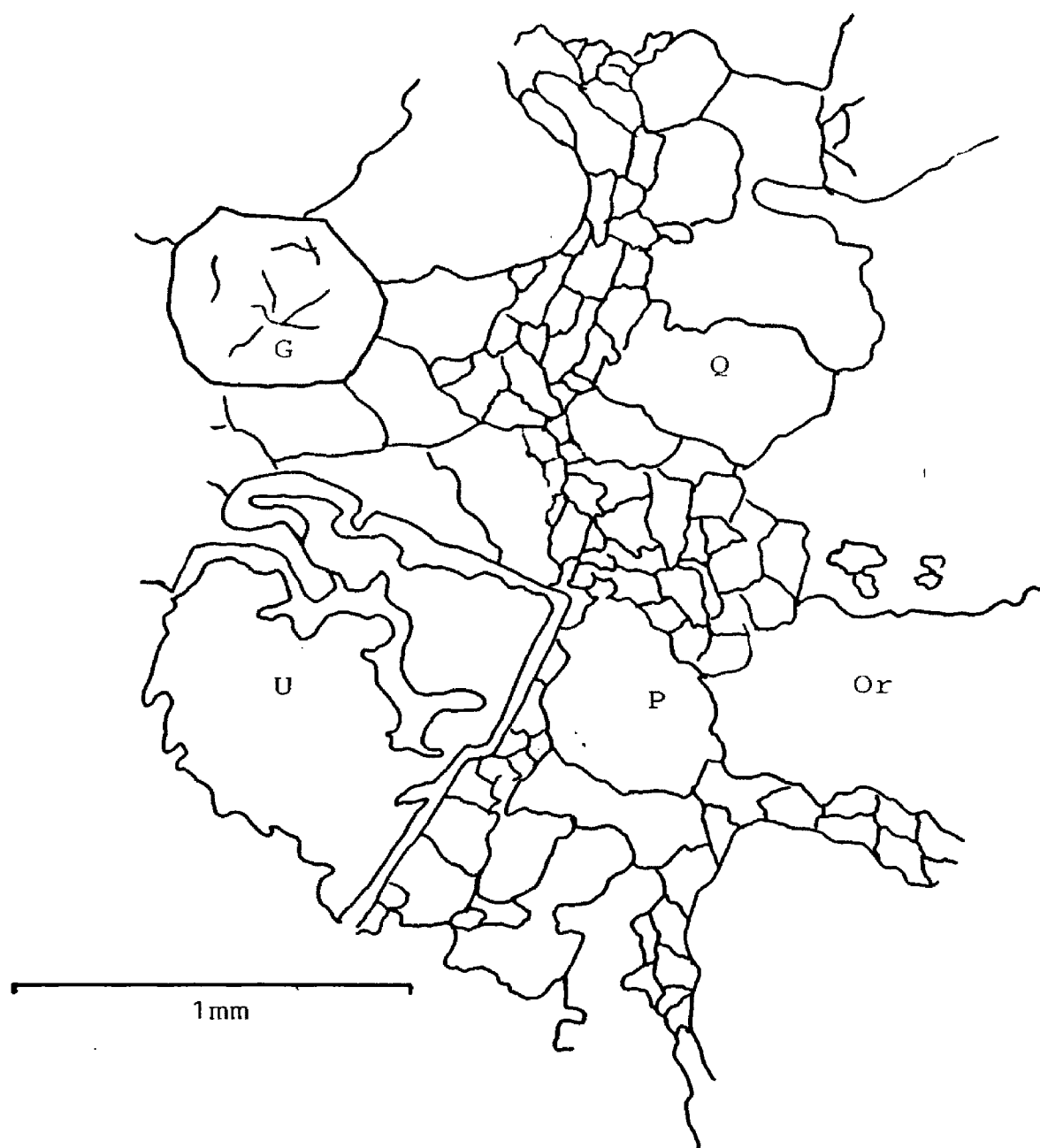
The uraniferous pegmatites have mineralogical zoning, well developed pegmatite textures, biotite envelopes, and no phaneritic margins (Fig. 4). Uranium is not uniformly distributed in these pegmatites, but occurs in discrete zones generally near the tops of the dikes. These zones range from 5 to 20 cm thick, and one to five of them may appear in a dike.

They constitute up to 20% of the dike, averaging approximately 5%. The remainder of a pegmatite with these zones also shows anomalous readings on a scintillometer. Analyses of grab samples show these zones contain up to 2650 ppm uranium (0.26%), though values above 1000 ppm are rare. They have little thorium, producing high U:Th ratios of up to 50:1. The uraniferous zones invariably have high garnet percentages (5-25%), and uncommonly large amounts of the accessory minerals apatite, magnetite and pyrite. The relative percentages of the major minerals vary little from the rest of the dike and from other non-uraniferous dikes, except for a tendency to contain slightly more orthoclase.

The uranium occurs as discrete grains of beta-uranophane, a hydrated calcium uranium silicate,  $\text{Ca}(\text{UO}_2)_2\text{Si}_2\text{O}_7 \cdot 6\text{H}_2\text{O}$ , identified by its X-ray powder-camera diffraction pattern. Petrographic observation shows that the mineral forms intergrown rectangular crystals that replace cubic crystals (Fig. 9). With incomplete replacement, remnants of a black opaque mineral have a steel gray reflection, and no hematite rim as all magnetite present shows. Beta-uranophane typically occurs as an alteration mineral of uraninite (Fronde1, 1958), as suggested here by the cubic crystal outline, reflectance, and lack of hematite alteration. The replaced uraninite occurs interstitially to feldspars and quartz, and in some cases as inclusions in garnet. Autoradiographs show uranium also occurring along some fractures in feldspars and disseminated in orthoclase.

High uranium concentrations of 500 - 2550 ppm with U:Th ratios of 30-40:1 occur in the biotite envelopes. Every uraniferous pegmatite

Figure 9. Uraninite replaced by beta-uranophane



U=beta-uranophane  
Q=quartz  
G=garnet

Or=orthoclase  
P=plagioclase



has a well-developed biotite envelope, and conversely, every well-developed envelope occurs with a uraniferous pegmatite. The exact mineralogy of the uranium is not known. Biotite grains include fine-grained black opaque minerals with a steel gray reflectance that could be uraninite. Autoradiographs show at least some are radioactive. Attempts to positively identify them did not succeed. A secondary yellow mineral, presumably beta-uranophane, occurs as a thin coating along biotite cleavages.

Secondary alteration affects the uraniferous dikes. Beta-uranophane replaces uraninite, chlorite pseudomorphically replaces biotite, hematite rims magnetite, and feldspars show minor sericitization. As this alteration is restricted to the pegmatite dikes and is generally lacking in other rocks, I infer that trapped aqueous solutions from the pegmatites caused it.

#### Controls on Uranium Distribution

The lack of uranium in granitic textured dikes, low concentration in the pegmatites with granitic margins, and high concentration in dikes with good pegmatite textures, well developed biotite envelopes, and no phaneritic margins demonstrates a direct relationship between uranium content and intensity of features attributable to an aqueous phase. The aqueous phase of a pegmatite system serves as a powerful solvent that extracts portions of various constituents from the viscous melt and serves as an avenue for ready movement from one part of the system to another. Partitioning of these constituents into the aqueous phase

occurs immediately upon the appearance of this phase, and increases as the amount of aqueous phase increases (Jahns and Burnham, 1969). Uranium and thorium behave essentially identically in a reduced state, due to their similar charges and ionic radii. Magmatic processes do not separate them from each other, and they are very insoluble in non-oxidizing aqueous fluids. Given oxidizing conditions and a means of transport, these elements do separate.  $U^{+4}$  goes to  $U^{+6}$ , a state chemically unavailable to thorium, becomes soluble, and dissolves in the aqueous phase, leaving the thorium behind (Whitefield and others, 1959). Subsequent crystallization and/or precipitation produces uranium concentrations with high U:Th ratios. Correlation of uranium with an aqueous phase, and the high U:Th ratios suggest such a scenerio occurred in the Nancy Creek area.

Once the dikes began to crystallize, the uranium concentrated into zones along with other accessory minerals. Uraninite inclusions in garnet indicate that the uraninite crystallized early. Its association with other early crystallizing minerals such as apatite in upper zones of the pegmatites suggest that physical movement of the volatile phase concentrated the uraninite. Given sufficient time, aqueous fluids can migrate upward through the denser magma, and become concentrated in the structurally higher parts of the pegmatite (Jahns and Burnham, 1969). The presence of zoning and well developed pegmatite textures not present in most pegmatites suggest that the uraniferous pegmatites had sufficient time to form undisturbed.

Uranium occurrences display a strong lithologic affinity for the amphibolite. This distribution mimics the distribution of pegmatite dikes with well-developed textures, and thus the distribution of the better developed aqueous phases. As these phases carried the uranium, their affinity for the physical environment produced in the amphibolite (discussed earlier) caused the stratigraphic concentration of uranium. Chemical reactions such as hornblende to biotite, helped trap the uranium, but were not the primary cause of concentration.

The aqueous phase concentrated uranium in quantities up to 2600 ppm into 5% of the volume of individual pegmatites. This occurred in approximately 2% of the total dikes. If the amount of uranium concentrated in these zones is evenly redistributed over the entire dike system, it adds less than 3 ppm to the uranium content of the average dike. Add that 3 ppm to the 5-10 ppm in the fine-grained dikes, and to the 10-15 ppm in most of the pegmatites, and the dike system contains 3-6 times the 3-5 ppm uranium of an average granite.

## CHAPTER V

### TIMING OF GEOLOGICAL EVENTS

The first event in the local history to consider is the formation of the protoliths for the metamorphic rocks. Their tentative correlation with pre-Beltian basement rocks and the preliminary whole rock Rb-Sr dates of 600-1200 m.y. (Cheney, in press) place the protoliths as Precambrian (Table 1). Sedimentary layers, now found east and west of the study area, were deposited on top until Late Triassic (Bowman, 1950; Parker and Calkins, 1964; Fox and others, 1977). A depositional hiatus followed, broken by the formation of the Eocene O'Brien Creek Formation, Sanpoil volcanic rocks, and the Klondike Mountain Formation (Fox and others, 1977; Cheney, in press).

Metamorphism began after the Late Triassic, as it affects Late Triassic formations (Fox and others, 1976, 1977). Amphibole and biotite from amphibolites of the Kettle Dome give K-Ar dates of 67 m.y. and 50 m.y. respectively (Engels and others, 1976). Their discordance probably represents slow cooling of the regional metamorphism in the Eocene. Intrusive rocks on the western margin of the Kettle Dome have similar cooling dates, indicating a concurrent end to the plutonic activity.

As features related to the emplacement of the Kettle Dome deform metamorphic textures (this paper; Donnelly, 1978), the emplacement began

Table 1. Timing of Geologic Events

	Precambrian	Cambrian--- Triassic	Jurassic	Cretaceous	Paleocene	Eocene	Oligocene	References
Formation of metamorphic protoliths	- - - - -							Cheney (in press)
Deposition of overlying strata		_____						Bowman, 1950; Parker and Calkins, 1964; Fox and others, 1977; Cheney, in press
Plutonism			- - - - -	_____	_____	_____	- -	Cheney (in press), Fox and others, 1977
Regional Metamorphism			- - - - -	_____	_____	_____	- -	Fox and others, 1977 and 1976; Engels and others, 1976
Emplacement of uraniferous dikes					- - - - -	_____	- -	This paper; Donnelly, 1978
Emplacement of the Kettle Dome			. . . . .	. . . . .	. . . . .	_____	- -	Cheney, 1979 and in press; Fox and others, 1976

after the onset of metamorphism. Fox and others (1976) postulate a pre-48 m.y. age of emplacement for the Okanogan Dome to the west, and by association, for the Kettle Dome. They base this on nearby undeformed Eocene formations and a K-Ar date on the Swimptkin Creek pluton which intrudes the Okanogan Dome. Cheney (in press), however, notes the presence of identical Eocene formations as young as 41 m.y. in synclinal structures both northeast and west of the anticlinal Kettle Dome. He suggests the emplacement of the dome separated these once-continuous formations and that the dome formed in the Late Eocene. Textures and structures indicate the uraniferous pegmatites formed during the formation of the dome (this paper; Donnelly, 1978), necessitating an Eocene age for them also.

## CHAPTER VI

### DISCUSSION

#### Genesis of the Dikes

There are four ways to produce granite dikes with granitic to pegmatitic textures in metamorphic rocks, two in situ and two external processes. They may form in situ through either anatexis or metamorphic segregation, or they may come from an external metasomatic or magmatic source. Field and petrographic evidence eliminates all but the external magmatic source for the main dike system.

#### In situ Processes

Anatectic processes could not operate in the highest three metamorphic units as metamorphic conditions there never reached an appropriate grade. Limited anatexis could occur in the lower quartzite unit, which lies just below the sillimanite-orthoclase isograd. Sufficient melting to produce the necessary amount of pegmatite magma could not have occurred because of the quartzite- and marble-dominated lithology. The reactions for when the pelitic units in the quartzite entered sillimanite-orthoclase grade produced textures that show only minor movement of material.

The amphibolite and eastern quartzite do not have compositions that could produce by metamorphic segregation the amount of felsic material required. Crosscutting relationships, chilled margins, and dike/country rock reactions indicate the presence of a significant quantity of magma,

and a change in overall composition in the amphibolite and quartzite near the dikes. In contrast, metamorphic segregation produces only very minor amounts of liquid, if any, and no overall compositional changes (Yardley, 1978).

Dikes in the biotite-plagioclase gneiss, excluding dikelets 2-4 cm thick, show similar contact relationships to the country rock, necessitating a melt as their source, not metamorphic segregation. The smaller 2-4 cm dikelets contain pegmatitic orthoclase, quartz, and minor albite and garnet. Many, but not all, are clearly connected with larger dikes, and in general, they concentrate in the same areas as the intrusive dikes. Secondary overgrowths on primary orthoclase, and albite-rich rims on plagioclase occur in the gneiss immediately adjacent to the dikelets. This indicates metasomatic addition of material to the rock from the dikes, whereas metamorphic segregation operates in the other direction. Also, in metamorphic segregation, a melanosome forms, and the plagioclase composition of it differs very little, or not at all from the plagioclase composition in the leucosome (Yardley, 1978). However, no melanosome exists, and plagioclase of the biotite-plagioclase gneiss ( $An_{30}$ ) differs sharply from that of the dikelets ( $An_{10}$ ). The addition of material, lack of distinct melanosomes, and differing plagioclase compositions argue against local metamorphic segregation.

If metamorphic segregation could extract very minor amounts of material from a large volume of rock, including a preference for Na over Ca, and concentrate them in distinct bands, the paleosome composition



would change almost unnoticeably and no distinct melanosome would form. This concentrating process may affect the rock neighboring the leucosomes, causing the secondary overgrowths. In this manner, metamorphic segregation could produce the dikelets that are not directly associated with larger dikes.

I prefer to interpret the halo surrounding the dikelets as a metasomatic halo caused by the intrusion of the dikelets into the rock. This halo and the close proximity of the dikelets to larger intrusive dikes, and a character indistinguishable from similar dikelets that are apophyses of dikes lead me to conclude that these seeming unattached dikelets are part of the intrusive dike system. As they may form pegmatitic bands 2-4 cm thick and up to 2 m long, they probably formed from low-viscosity, volatile-rich fluids derived from pegmatite magmas.

#### External Processes

As in situ processes can not provide the necessary granitic material, the dikes must originate from a source external to the exposed metamorphic section. As discussed previously, the dike system needs a viscous, water-undersaturated magma that differentiates into a water-saturated system to produce the textures and relationships described. Metasomatism has occurred, but its activities result from the aqueous fluids derived from the pegmatite magma.

Magma for dikes has two possible general sources. It may either arise as an offshoot from a larger plutonic source such as a stock or batholith and be termed igneous, or arise anatectically, forming a complete system

unto itself. As neither contemporaneous plutonic rocks nor an anatectic source crop out in the map area, a source outside the area, or at depth must be considered. The genetic process for the Nancy Creek dikes must produce an undersaturated, potassium-rich, low-calcium granite magma. The process must account for the timing of dike emplacement, their regional distribution and association with metamorphic rocks, the uranium content, and the limited compositional range.

Distribution of intrusive units. Cheney's (in press) regional map (Fig. 2) shows intrusive rocks concentrated in the northwest corner of the Kettle Dome. They vary in composition from quartz monzonite to granodiorite (Parker and Calkins, 1964). They contain miarolitic cavities and intrude Tertiary volcanics in the Republic Graben, indicating a shallow level of emplacement. Their descriptions mention no pegmatite phases, and these units truncate pegmatite-bearing migmatites. As these intrusions cut domal structures and are shallow, they appear to have formed after the dome, though this conclusion is not decisive. Other similar intrusions border the dome along its western margin. Their contact and temporal relationships to the dome are unknown.

In the southern two-thirds of the dome six small intrusive bodies represent the only plutonic rock present other than the dikes. Either hornblende or biotite tend to dominate their mafic mineralogy. They cut across metamorphic structures, and may be either foliated or massive (Cheney, in press). Their compositions and relationship to the large intrusive units are unknown. The massive to foliated nature of these intrusions suggest contemporaneity with the dikes.

Consideration of an Igneous source. As major intrusive units crop out along the western and northwestern border of the dome, and minor ones crop out within the dome, an igneous source is possible for the dikes. A direct relationship between the small intrusions and the bordering intrusions would imply a large granitic body underlying the Kettle Dome. If no such relationship exists, the small intrusions within the dome could represent the top of an iceberg, and a batholith could still underlie the dome. Plutonic rocks core many Shuswap domes, and the Bitterroot Dome (Hyndman, 1979). In the Bitterroot Dome, shearing is contemporaneous with the last stages of consolidation of the Idaho batholith (Hyndman, 1979). This period of crystallization could produce late-stage differentiates, possibly explaining the felsic, potassium-rich composition of the dikes at Nancy Creek compared to the composition of the intrusions. Such a scenario would also occur after peak metamorphism as seen in the Kettle Dome. Uranium often concentrates in these late intrusive stages due either to movement with volatiles, or crystallization processes excluding it from crystallizing rock because of its large ionic size and high valence charge.

Postulating a large igneous body underneath the Kettle Dome would provide a genetic model for the granite dikes that could explain the composition of the dikes, their regional distribution, association with metamorphic rocks, timing of emplacement, and uranium content. This argument, however, does have some serious weaknesses. A batholith does not necessarily underlie the Kettle Dome. The small intrusive bodies

may not be the top of an iceberg, but just localized magmatic bodies formed anatectically with no connection to a larger body. Any connection between them and the bordering intrusions to the west is hypothetical at this time. The present poor understanding of the timing of the bordering intrusions seems to indicate they formed after the dome, and consequently after the dikes. The dikes in the Nancy Creek area show no local concentration relative to a local intrusive body just north of the map area. No pegmatite and especially no granitic-textured dikes of compositions comparable to the bordering intrusions exist, and no dikes directly associated with them are described in the literature.

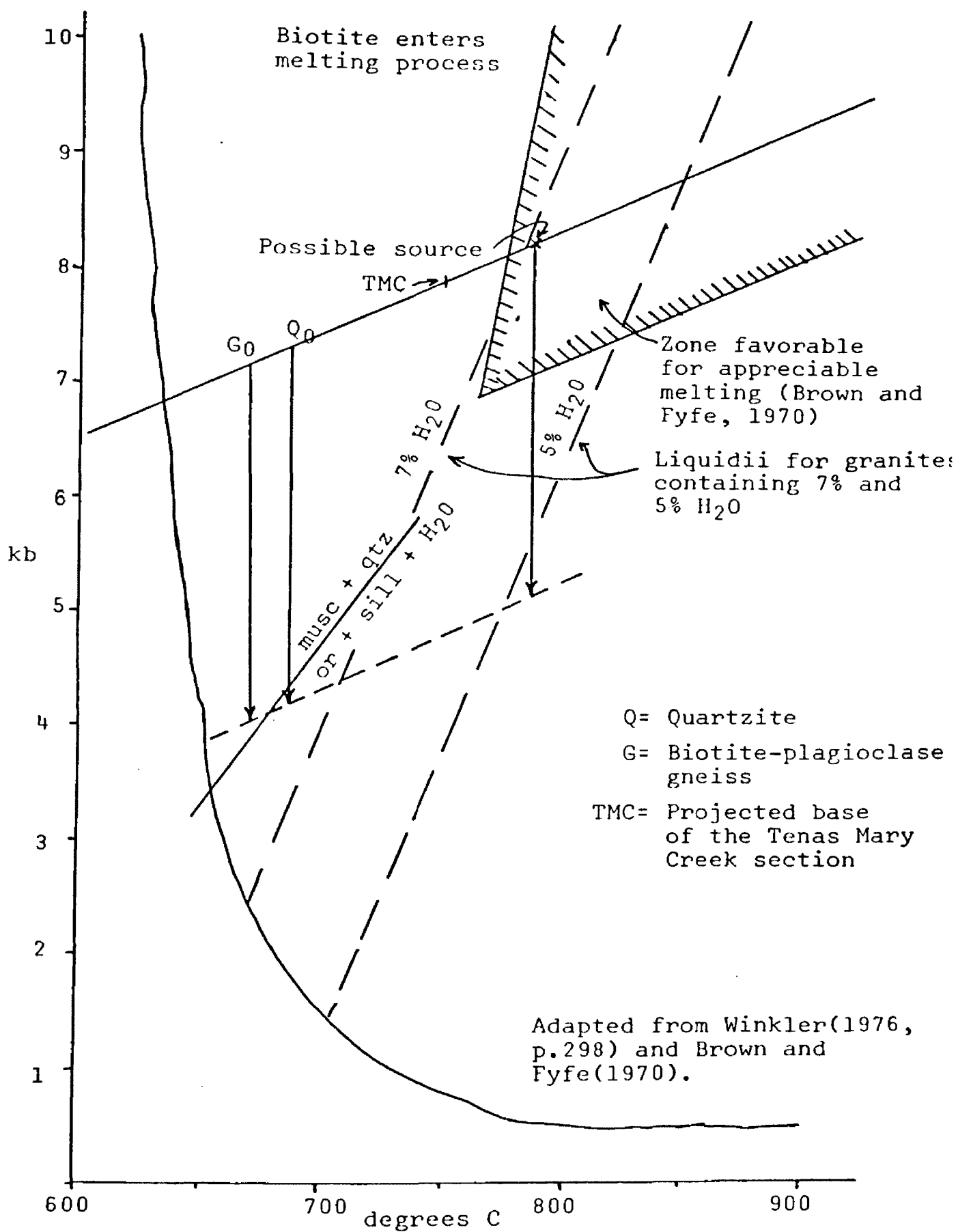
Textures, cross-cutting relationships, and associated rock types indicate a shallow depth of emplacement for the intrusions in the northwest corner (Parker & Calkins, 1964), yet metamorphic conditions suggest greater depths for the pegmatites. The intrusions truncate metamorphic rocks containing dikes, establishing their relative ages. Dikes in undiminished quantities occur 35 km away from these intrusions. The dikes could form as early precursors to the intrusions, but their unchanging occurrence over such distances remains unexplained unless hypothetical intrusions lie below.

Consideration of a metamorphic source. The regional distribution of dikes in metamorphic rocks suggests a possible metamorphic genesis for them. Rocks at the base of the Nancy Creek section enter high-grade metamorphism by the reaction muscovite + quartz  $\rightarrow$  sillimanite + orthoclase +

water. In rocks of appropriate composition, incipient melting marks this transition (Winkler, 1976, p. 83). The relationships of dikes to shear zones, and the structural analysis of Donnelly (1978) indicate the dikes intruded the metamorphic section during formation of the Kettle Dome. The shearing occurs near the final stages of dome formation. The exact means of this formation is not completely understood. Interpretation of the eastern border of the dome as a decollement (Cheney, 1979) implies the removal of a sedimentary section 31,000 feet thick (Bowman, 1950), probably followed by a diapiric rise of the dome. Analysis of changes in temperature and pressure conditions during this process provides insight for a possible anatectic source.

The following considerations allow a close approximation of the pressure and temperature conditions during shearing. As the shearing is a late stage in the formation of the dome, a drop in pressure accompanies it. During the shearing, the quartzite crossed the boundary for muscovite + quartz  $\rightarrow$  sillimanite + orthoclase + water. Muscovite plus quartz still exist in equilibrium in the biotite-plagioclase gneiss 100 m above it, so the gneiss did not cross that line. As minor anatexis occurred in the quartzite, it must have been above the quartz-albite-orthoclase-water solidus. The overlying gneiss may also have been above that solidus because the anorthite content (Winkler, 1976, p. 293), lack of indigenous orthoclase, and no water-liberating reaction inhibit melting. In Figure 10, points  $G_1$  and  $Q_1$  indicate the pressure and temperature conditions during shearing of the gneiss and quartzite respectively. Their

Figure 10. Granite Melting Curves



temperatures may range 20°C either up or down, with a corresponding range in pressure, but this will not substantially alter the argument. As the removal of a 31,000-foot section corresponds with a 3 kb pressure drop,  $G_0$  and  $Q_0$  describe plausible conditions prior to detachment.  $G_0$  and  $Q_0$  should be at a higher temperature because cooling probably accompanied the pressure drop. Leaving them where they are compensates for a possible lower temperature for  $G_1$  and  $Q_1$ .

The shaded area marks the most likely conditions for major production of natural granites. Its left-hand border indicates the beginning of the incongruent breakdown of biotite to supply water for the fusion process (Brown and Fyfe, 1970). To the left of this line, only the breakdown of muscovite supplies water for fusion, and slightly potassic granite melts may form. To the right, biotite incongruently enters the fusion process, followed by phlogopite and hornblende at higher temperatures, the melt composition changing from granite to granodiorite.

The base of the exposed Tenas Mary Creek section falls outside this zone, and therefore would not produce substantial quantities of magma. Minor anatectic migmatites may form in situ, however, where muscovite breakdown releases minor amounts of water. A potential source (X) falls in this shaded zone. As the pressure drops, X moves farther from the line marking the start of biotite instability. This results in more biotite entering the melt, adding more water to that already available from the breakdown of muscovite and earlier biotite. Considering the greater abundance of biotite compared to muscovite, its breakdown may easily

double or triple the availability of water and consequently double or triple the amount of melting. By dropping the pressure the full 3 kb, conditions go from a point just below the granite liquidus with 7% water to a point just above the liquidus for 4% water (Winkler, 1976, p. 306). This increased activation of water allows melt production of another 50%. The isothermal drop in pressure thus permits 3 to 5 times the initial amount of melting by changing the amount and activity of the available water.

The exact amount of melt depends on the initial rock composition and total water available. If water released from biotite and muscovite breakdown amounts to 0.2% at the original pressure, 4% of the rock may melt during the three kilobar pressure drop.

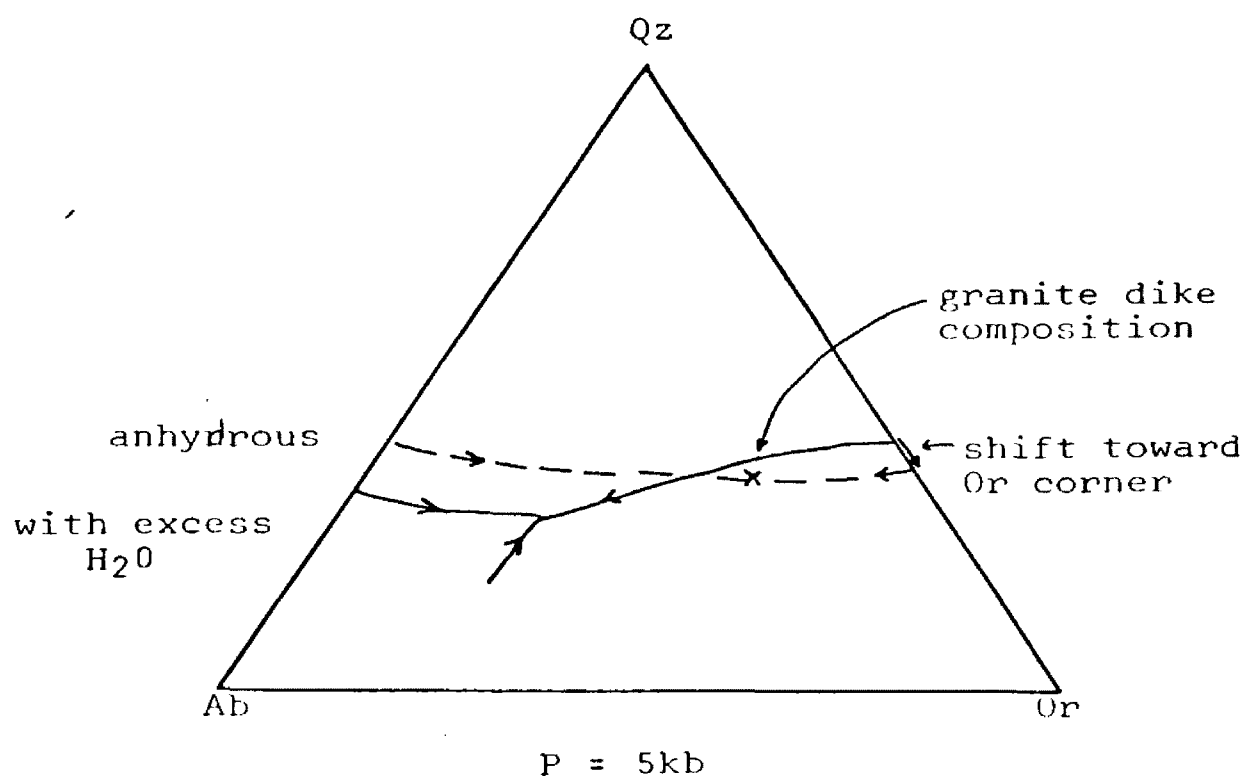
In an An-Ab-Or-Qz tetrahedron, the dike composition plots on a cotectic surface, just to the Or-Ab side of the cotectic line (Fig. 5 in Crystallization Path section, Wyllie, 1977). Comparing the dry Ab-Or-Qz system at 5 kb to the same system with excess water, the cotectic line shifts slightly toward the Or corner in the area where the dike composition plots (Wyllie, 1977). Projecting this displacement into the tetrahedron plots the dike composition close to the cotectic line (Fig. 11). As water availability and temperature limit the amount of melting, the melt produced should remain on the cotectic line, producing a narrow range in compositions as observed in the dikes.

This genetic model of generating granitic magma in high-grade metamorphic terrane by dropping the pressure predicts the metamorphic reactions



Figure 11.

Projection of An-Ab-Or-Qz Field Boundaries onto an Ab-Or-Qz Triangle (Adapted from Wyllie, 1977)



observed in the biotite-plagioclase gneiss and the quartzite, and lack of locally generated migmatites. It also accounts for a source "at depth", the composition of the dikes, their regional distribution, and temporal associations with the dome emplacement.

Anatectic concentration of uranium. In metamorphic rocks, Lambert and Heier (1967) have shown that pyroxene granulite facies rocks contain less uranium than their lower grade analogs. Koslov (1977) claims that with increasing pressure and temperature conditions, the content of uranium in corresponding rocks gradually decreases. The uranium found along grain boundaries or as interstitial minerals decreases with increasing metamorphic grade, leaving only the uranium in accessory minerals. Since water constitutes the main phase leaving metamorphic rocks with increasing grade, the uranium probably moves with it. As anatexis concentrates the water into the melting fraction, it follows that uranium also concentrates there.

#### Extrapolation of the Anatectic Genesis Model to the Rest of the Kettle Dome

The foliated to unfoliated nature of the small plutonic bodies in the dome (Cheney, in press) and similar relationships to cataclasis in the igneous terrane in the northwest corner of the dome suggest a contemporaneity to the dikes. The small scattered bodies may form in a fashion similar to the dikes but had more water available to them, or melted at a deeper level, accounting for their greater volume. The intrusions in the northwest corner lie closer to the Okanogan Dome, and the axis of the Omineca crystalline belt (Fox and others, 1977). A

higher heat flow would be expected along this axis. This would push pressure and temperature conditions further into the zone favorable for melting, resulting in a higher percentage of melting, producing the trend from granite to granodiorite seen in this part of the dome.

## CHAPTER VII

### SUMMARY AND CONCLUSIONS

Granite dikes intrude the upper-amphibolite-grade metamorphic rocks of the Kettle Dome. They formed contemporaneously with the emplacement of the dome, preferentially intruding structurally weak shear zones in the biotite-plagioclase gneiss, the gneiss-amphibolite contact where relative movement occurred, and the more brittle amphibolite. Three textural types of dikes occur: granitic, aplitic, and pegmatitic. The undersaturated original magma formed the granitic dikes. Crystallization processes concentrated the water to the saturation point, causing the appearance of an aqueous phase. This phase caused the formation of the common pegmatite-cored dikes, and the rarer completely pegmatite dikes. Aplite dikes invariably have strong cataclastic textures, and formed due to a sudden loss of the aqueous phase, possibly caused by a decrease in confining pressure during shearing. The pegmatite magma (magma plus the volatile phase) migrated to the amphibolite, where shearing had created a better crystallization environment as compared to the rigid gneiss below. The impermeable Eastern Quartzite capped the amphibolite, and helped to contain the pegmatites.

Zones in some pegmatites contain highly anomalous concentrations of uranium (up to 0.25% or 2500 ppm), whereas the overall dike system contains only 10-15 ppm. The uranium occurs in the pegmatites with the coarsest pegmatitic texture, and the only mineralogical zoning in the

system. These dikes concentrate in the amphibolite, and have the thickest biotite reaction envelopes. Concentration of uranium correlates directly with the movement of the aqueous phase in the pegmatite system. Under oxidizing conditions, the uranium partitions selectively into the aqueous phase when it arises, and moves in solution with it. Its high mobility allows the phase to escape to the structurally preferable amphibolite. During crystallization of the pegmatite, the aqueous phase physically concentrates the early-crystallizing uraninite into zones with garnet, magnetite, and apatite. The uranium remaining in solution moves into the metasomatic envelope where it is trapped along biotite cleavage planes.

#### Magma genesis

Field and petrologic evidence rule out a metasomatic, and an in place metamorphic segregation or anatectic genesis for the main dike system. Although questionable, metamorphic segregation possibly formed small dikelets in the biotite-plagioclase gneiss. Some of the dikes in the gneiss may have formed with late stage fractionation of the gneiss, as it is an orthogneiss. The main dike system formed from a magma generated outside the field area. Crystallization processes concentrated water to a saturated condition in some dikes, and produced the varied textures.

Two genetic possibilities for the magma and their supporting evidence have been presented. In one, the magma came from a postulated batholith that cores the Kettle Dome. In the other, extrapolation of metamorphic

conditions to below the exposed metamorphic section, combined with a drop in pressure correlative to tectonic unloading of the Kettle Dome produces conditions favorable for anatectic melting. Both models can explain the timing, composition, regional distribution, association with metamorphic rocks, and the uranium content of the dikes. Both are also based partly on inference.

I prefer the anatectic pressure-drop model. It provides a unified model intimately linked with its metamorphic and structural setting. As temperature increases with depth beyond the sillimanite zone now exposed at the surface, the temperature required existed. As a pressure change accompanies tectonic unloading of the dome, the triggering mechanism existed. Thus a process, and a means of initiating that process existed contemporaneously. The igneous model relies in part on analogy to other gneiss domes, and those analogies just may not fit.

By accepting the anatectic model, this thesis illustrates how anatectic processes, driven by a drop in pressure, can produce granite magma and concentrate uranium in it. The rise of the Kettle Dome during emplacement provides the pressure change, and structurally prepares an environment for dike formation. It also demonstrates the variety of ways water can effect petrogenetic processes. Water aided the melting, concentrated uranium in it, produced the varied dike textures, concentrated the uranium again into the aqueous phase, and then either physically concentrated it into zones, or transported it in solution to where biotite trapped it in the metasomatic envelope.

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